Use of microtubes in the design of optimized trickle irrigation network

Mohammed Abdel-Rahman Ibrahim

Civil Engineering

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Abstract

In a country like Saudi Arabia where water is premium and brackish, trickle irrigation systems become an attractive alternative for conserving water. Usually microtubes are used as emitters in the trickle irrigation network to deliver the same amount of water throughout the network. Microtubes have many advantages compared to other emitters. A comprehensive methodology for the design of microtube trickle irrigation system is, therefore needed.

A chart and nomographs have been developed for the design of microtube emitters to deliver the same amount of discharge by all microtubes along the network. In the case of coiled microtubes, design chart and nomographs have been modified. A computer program too has been developed for the designers who have access to computing systems for the design of microtube emitters with and without coils.

For the design of laterals a computer program has been developed. All the lateral design cases have been taken into consideration in the development of the program.

Considering the cost of the network, optimization techniques have been used to minimize the cost of main, submains and pumping station while satisfying the design requirements.

Use of Microtubes in the Design of Optimized Trickle Irrigation Network

by

Mohammed Abdel-Rahman Ibrahim

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

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DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
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In

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This thesis, written by **Mohammad Abdel Rahman Ibrahim** under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of the College of Graduate Studies, in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

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Dedicated to

The soul of my father, my mother,
my wife and my son

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May all praise and thanks (first and last) be to ALLAH, The Almighty, with whose gracious help it was possible to accomplish this work.

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In a country like Saudi Arabia where water is premium and brackish, trickle irrigation systems become an attractive alternative for conserving water. Usually microtubes are used as emiters in the trickle irrigation network to deliver the same amount of water throughout the network. Microtubes have many advantages compared to other emiters. A comprehensive methodology for the design of microtube trickle irrigation system is, therefore needed.

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MASTER OF SCIENCE DEGREE

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
Dhahran, Saudi Arabia

January 1989

الخلاصة

اسم الطالب : محمد عبد الرحمن ابراهيم

عنوان الدراسة : استخدام الأنابيب ذات الأقطار الصغيرة في تصميم شبكة الري بالتنقيط المثلى

حقل التخصص : هندسة مدنية

تاريخ التخرج : يناير ١٩٨٩م

عندما تكون المياه شحيحة ومالحة كما هو الحال في المملكة العربية السعودية ، ويكون استخدام الري بالتنقيط ذو فائدة كبيرة في المحافظة على كمية المياه . وتستخدم الأنابيب ذات الأقطار الصغيرة كبديل للرشاشات في شبكة الري بالتنقيط للقيام بتوزيع مياه الري بصورة منتظمة في جميع أنحاء شبكة الري . وتتميز الأنابيب ذات الأقطار الصغيرة بمزايا عديدة بمقارنتها بأنواع الرشاشات الأخرى . ولهذا فمن الطبيعي وجود طريقة متكاملة لتصميم شبكة الري بالتنقيط ذات الأنابيب الصغيرة .

تم استنتاج منحنيات لتصميم الرشاشات ذات الأنابيب الصغيرة في شبكة الري بالتنقيط . وهذه المنحنيات تم استنتاجها لتعطي توزيع منتظم لمياه الري في جميع أنحاء الشبكة . أما في حالة لف الأنابيب الصغيرة ، فقد تم استنتاج منحنيات معدلة للتصميم . وبالنسبة للمصممين الذين يملكون أجهزة حاسب آلي ، فقد تم عمل برنامج لتصميم هذه الرشاشات في حالتي لف وعدم لف الأنابيب الصغيرة .

كذلك تم عمل برنامج على الحاسب الآلي لتصميم أنابيب الموزعات . آخذا في الاعتبار كل حالات التصميم المختلفة .

ولكي يكون التصميم اقتصادي ، فقد تم استخدام التقنية المثالية لتقليل تكلفة انشاء المواسير الرئيسية والفرعية ومحطة المضخات ، وفي نفس الوقت تمت المحافظة على متطلبات التصميم .

درجة الماجستير في العلوم
جامعة الملك فهد للبترول والمعادن
الظهران – السعودية
يناير ١٩٨٩م

CHAPTER 1

INTRODUCTION

1.1 TRICKLE IRRIGATION

The use of trickle (or drip) irrigation has become one of the most popular systems of irrigation, especially in areas where water is premium. Trickle irrigation is the application of water to agricultural soils by means of emiters (dripers) to cause wetting of only the part of the soil at the base of the plant (the plant root zone) (1,2).

Normally the system possesses a fertilizer injection system supplying plants with needed nutrients. A filter is used in the system to remove suspended materials, organic matter, sand and clay reducing blockage of the emiters. Along with pumping station; control valves, measuring devices and pressure controls are generally installed to the system providing it with needed pressure heads (1,2,3,4).

Emiters are the plants' point sources of water and they should be designed to provide small and equal amounts of discharges, thus nearing the consumptive use of plants. Emiters are of many kinds such as microtubes, orifices, nozzles, porous pipes, etc. (1,5).

Emiters receive water from the laterals, which are usually made of plastic tubing ranging in diameter from 12.0 mm to 32.0 mm. Laterals with only one diameter of tubing are normally recommended to simplify

installation and maintenance; and provide better flushing characteristics (1,2,6).

Trickle irrigation system features laterals that extend from either one or both sides of the submain. Submain is either of medium density polyethylene (PE) or rigid PVC (polyvinyl chloride) ranging in diameter from 20.0 mm to 80.0 mm (1,7).

The mainline connects different submains to the water source. It is fabricated using stiffer materials as asbestos cement, rigid PVC or galvanized steel. The mainline diameter is usually of 50.0 mm and above (1,8). Figure 1.1 shows an example of a trickle irrigation pipe system network which consists of laterals, submains and main.

1.2 BENEFITS OF TRICKLE IRRIGATION

Trickle irrigation system could be considered as one of the most water saving systems , thus makes it an ideal one for areas with limited water. This system is also beneficial in temperate areas where other irrigation systems increase the amount of water loss by evaporation and/or deep percolation. The system has also the advantages of high water application efficiencies and savings (1,4,5).

Previous experience reveals that trickle irrigation gives greater crop yields and better qualities specially for those crops that contain considerable amount of moisture when harvested, and those having widely widely spaced plants (9,10,11,12,13).

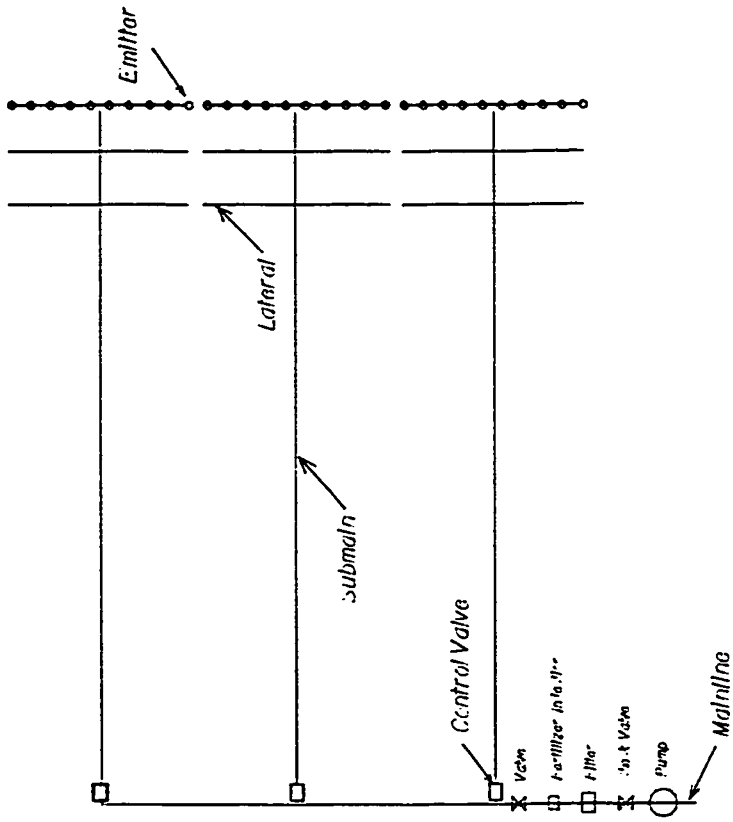


Figure (1.1) Trickle System Schematic

It is easy to manage a farm by using trickle irrigation system because many operations such as springing, harvesting, pruning, etc. can be performed at the same time (1,14).

Sprinkler irrigation is recommended for heavy soils and surface irrigation is recommended for light soils. Unlike sprinkler irrigation and surface irrigation, trickle irrigation can be used for both light and heavy soils (1).

Use of saline water is not recommended in sprinkler irrigation which causes leaf burn. However, saline water can be applied in trickle irrigation systems. Saline water should be applied with caution because salts may cause emiter clogging and requires frequent soil leaching to prevent salt accumulation in the soil (1).

1.3 PROBLEM STATEMENT

Blocking or clogging of emiters has for a long time been the obstacle in the development of trickle irrigation. Clogging occurs mainly due to passage of water through the very fine pores of the driper. The delivered water always contains suspended particles, salts and/or dissolved fertilizers, which creates severe maintenance problems that require tedious effort and skilled man-power. This is specially true in countries like Saudi Arabia where man-power is expensive and water is brackish. In addition to emiter clogging, uneven emiter flow is another major problem. This is because emiter flow changes as the

acting pressure head changes (14,15,16,17).

Also the procedures for the design of main and submains pipe network have been developed based on trial and error methods in which the designer selects pipes' diameters and checks whether the required pressure heads can be achieved. These trial and error methods do not guarantee that the design minimizes the total cost of the network (7,8,18).

1.4 NEED FOR THE PROPOSED STUDY

Microtubes have been successfully used as emiters in trickle irrigation systems with the advantages of having the same discharge at all openings along the lateral and its susceptibility to clogging is insignificant (1,19).

Microtube design Charts that are currently available have a number of draw-backs. These draw-backs are discussed in details later. Literature survey shows that improved design Charts and Nomographs are needed.

To be flexible in lateral design, a procedure is developed to determine the parameters governing the design. These parameters are:

- operating head at the entrance of the lateral;
- emiter discharge and
- lateral diameter.

Furthermore; the procedure should consider microtube diameter, spacing of microtubes and land slope. To account for a multitude of combinations, it is apparent that a computer program is ideal for lateral design. Such a computer program will have the advantages of being accurate and fast.

It would be a very tedious task to design a pipe main and submains network based on economic considerations. It may need thousands of trials to obtain the most economic design. To ease the burden while still achieving an optimum solution, an optimization model can be set up and then be solved by means of a computer (4).

1.5 THE OBJECTIVE OF THE STUDY

The main purpose of this study is to device a procedure to minimize the total expenses of construction and installation of a trickle irrigation network while restoring the uniform distribution and plant water requirements. This goal is satisfied throughout the design of each component of the network.

Thus the specific objective of this study will be

1. To develop a design procedure to determine the appropriate microtube lengths. This will include:
    - a - development of a design Chart and Nomographs; and
    - b - development of a computer program.

2. Development of a computer program for the design of the lateral for three cases, where one determines:

   I : the required lateral diameter given the discharge and operating head at the lateral entrance;

   II : the required operating head at the lateral entrance given the discharge and the lateral diameter; and

   III : the required discharge given the operating head at the lateral entrance and the lateral diameter

   In addition to the above, the computer results will be experimently verified and the sensitivity of the system to various variables will be investigated.

3. Development of an optimum model for the design of main, submains and pumping station.

1.6 PROPOSED PROCEDURE

1 - Development of a design procedure to determine microtube lengths

Microtube lengths should be adjusted with the acting head at its inlet to deliver the same amount of discharges for all microtubes. Two design procedure will be developed for calculating the microtube length as follows:

a - Development of a Design Chart and Nomographs

Most designers may not have access to a computing system. Thereby, it is desired to develop simple Charts and Nomographs which may be used by designers to compute microtube lengths. The drawbacks in the previously developed design Charts are tried to be avoided.

b - Development of a computer program

For the designer who has access to a computing system; a computer program will be developed to determine the microtube lengths knowing the pressure head distribution along the lateral.

2 - Development of a computer program for lateral design

To make a complete design of microtubes, the head distribution along the lateral should be known which is a function of a number of variables (land slope, spacings between microtubes, microtube diameters, the discharge, lateral diameter and pressure head along the lateral).

In all, the following three design cases may arise :

Case I : determine lateral diameter assuming known discharge and total head at the lateral entrance.

Case II : determine the total head at the lateral entrance assuming known discharge and lateral diameter.

Case III : determine discharge assuming known total head at the lateral entrance and lateral diameter.

i- Experimental verifications

It is aimed to verify the correctness of the microtube design procedure by applying different pressure heads at the microtube inlet and measure the corresponding outlet discharges. It is also aimed to simulate field conditions in the laboratory by connecting microtubes to a lateral. Flows and pressure heads at the lateral inlet will be measured, this will verify correctness of the computer program for the lateral design.

ii- The system sensitivity

Since the system of equations have too many variables, it will be useful to know which variables are most important. This; while eliminating some variables that have minimal effects; will also help in operation and management of the system to take corrective measures.

3 - Optimum diameters of main and submains

It is proposed to use an optimization model to formulate the main and submains network design as a cost minimization problem with design requirements as constraints. Not only the cost due to change in diameters will be taken into consideration but the pump cost will also be considered.

CHAPTER 2

LITERATURE REVIEW

2.1 MICROTUBE EMITER

"During the last decade numerous trickle irrigation emiters with widely varying characteristics have become available. Some emiters are "pressure compensating" and others are not. Some emiters are self-cleaning or "flushing" and others clog easily and need sophisticated filtration. Some emiters are relatively expensive and some are very cheap" (20). Solomon (21), Karmeli and Keller (22) and Karmeli (23) list the desired qualities of a trickle emiter (24).

Most trickle emiter characteristics can be represented in the emiting flow regime by an exponential curve shown in Figure 2.1 of the form (20).

$$q = c\ H^{x} \qquad (2.1)$$

where

q = flow rate

H = operating total head

x = emiter exponent

c = a constant dependent on the emiter type and the units for q and H

Equation (2.1) shows that the outlet discharge is a function of the

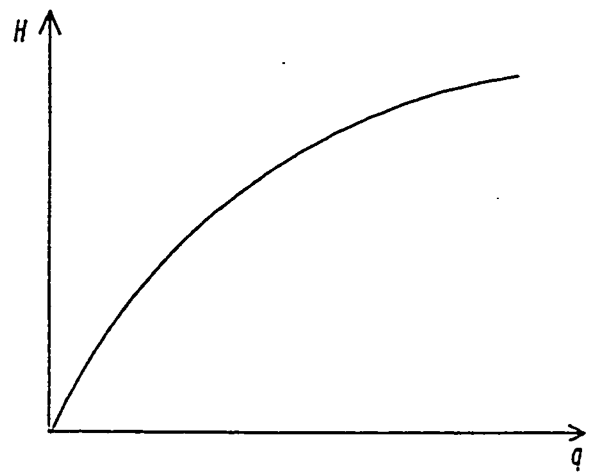


Figure (2.1) Emitter Flow Characteristc

operating total head. It can be easily seen that a high variation in total head causes non-uniform distribution of water flow. Most design recommendations do not allow more than 20% head variation (4).

"The simplest, cheapest, and forerunner of all the distributors is the microtube, which is a small bore black polyethylene tube of approximately 0.6 mm to 4.0 mm internal diameter. The discharge from a microtube varies according to the operating head, internal diameter, and length. In other words, for a given internal diameter the discharge of a microtube may be kept constant under various head conditions by adjusting its length. So, if the head distribution along a lateral is known, uniform distribution of water can be obtained by choosing the appropriate length of the microtube" (1).

In microtubes, the symbol (H_m) is given for minor head losses, while Khatri, defined (H_m) to include the velocity head and the minor losses due to the entrance and fitting (19).

The relationship between the total head at the inlet of the microtube (H) and the head losses through the microtube, shown in Figure 2.2, can be expressed by Equation (2.2) (19).

$$H = H_f + H_m \tag{2.2}$$

where

H = total pressure head in the lateral at the microtube inlet

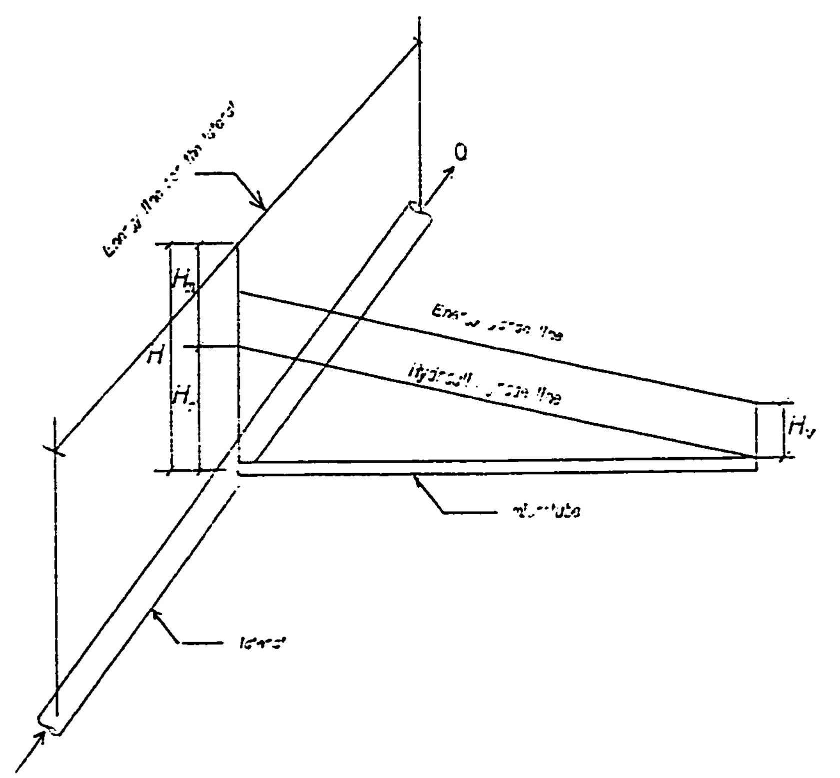


Figure 2.2: Energy and Hydraulic Grade Lines for Microtube

H_f = friction head loss

H_m = velocity head and minor losses

Laboratory experiments done by Khatri showed that Darcy-Weisbach equation can be used to represent **total head** drops for microtubes. This agrees with the research results by Paraqueima (25), and by Watters and Keller (26) for larger trickle irrigation tubing (4.0 mm - 16.0 mm). Khatri concluded that the friction head in Darcy-Weisbach is replaced by the **total head** where the minor losses are not separated. Darcy-Weisbach equation is expressed in by the following equation (27):

$$H = \frac{f\ L\ v^2}{2\ d\ g} \qquad (2.3)$$

where

H = operating total head

L = microtube length

v = flow velocity

Khatri also showed that the relationship between the friction coefficient and the Reynolds' number represents hydraulically smooth pipe, whereas Blasius equation can be used to determine the friction coefficient in turbulent flow. Blasius equation is represented by the following equation:

$$f = \frac{0.316}{R^{0.25}} \qquad (2.4)$$

where

f = friction coefficient

R = Reynolds' number

The Reynolds' number is expressed in the form of water discharge by the following equation:

$$R = \frac{4\,q}{\pi\,d\,\nu} \qquad (2.5)$$

where

q = microtube discharge

d = microtube diameter

ν = kinematic viscosity

Khatri, also showed that the straight line (for laminar flow in Moody diagram) can be used to determine the friction coefficient in laminar flow situation. Laminar flow straight line is expressed by the following equation (19,27):

$$f = \frac{64}{R} \qquad (2.6)$$

Based on his laboratory experiment, Khatri (19) deviced a design Chart for microtube design. Figure 2.3 shows this design Chart for all types of flow. This Chart has some draw backs which are:

- it was developed based on experimental formulae. These formulae may not be applicable for all types of microtubes;
- they need additional calculations and

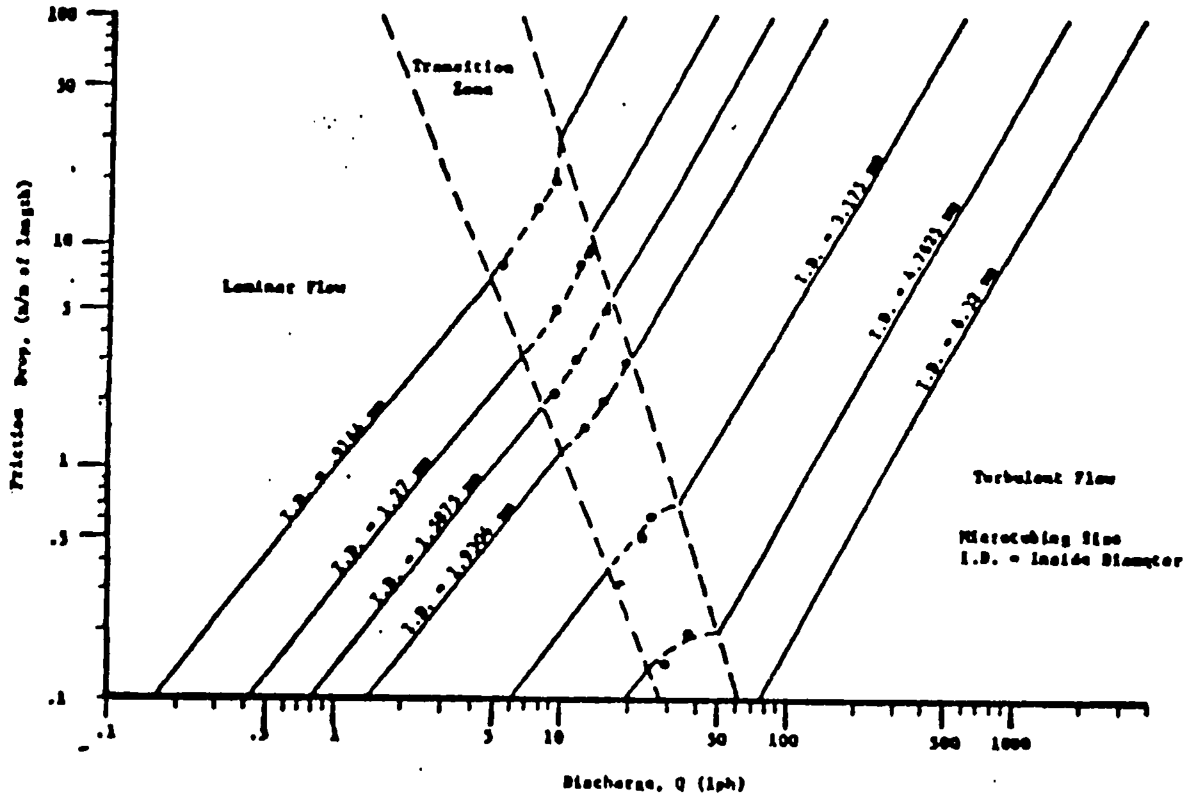


Figure (2.3) Microtube design chart by Khatri

- they are not applicable to include extra head loss.

FAO (1) published a group of design Charts for different microtube diameters for microtube design. Figure 2.4 shows one of these design Charts at a discharge of 4 l/h. These design Charts have the following draw backs:

- they need additional calculations;
- they are not applicable to include extra head loss; and
- large number of charts for different discharges make it difficult for searching and handling.

2.2 LATERAL

Many design procedures have been developed and practiced for the design of trickle irrigation laterals. Laterals are designed to deliver a reasonable uniform water distribution. The distribution uniformity of irrigation water is expressed by Christiansen uniformity coefficient (U_c) (4,6). Christiansen uniformity coefficient is calculated from the following equation:

$$U_c = 100 \left(1 - \frac{\Delta y}{\bar{y}} \right) \qquad (2.7)$$

where

U_c = uniformity coefficient.

Δy = Mean deviation of y.

$\bar{y}$ = mean of the depth of irrigation water.

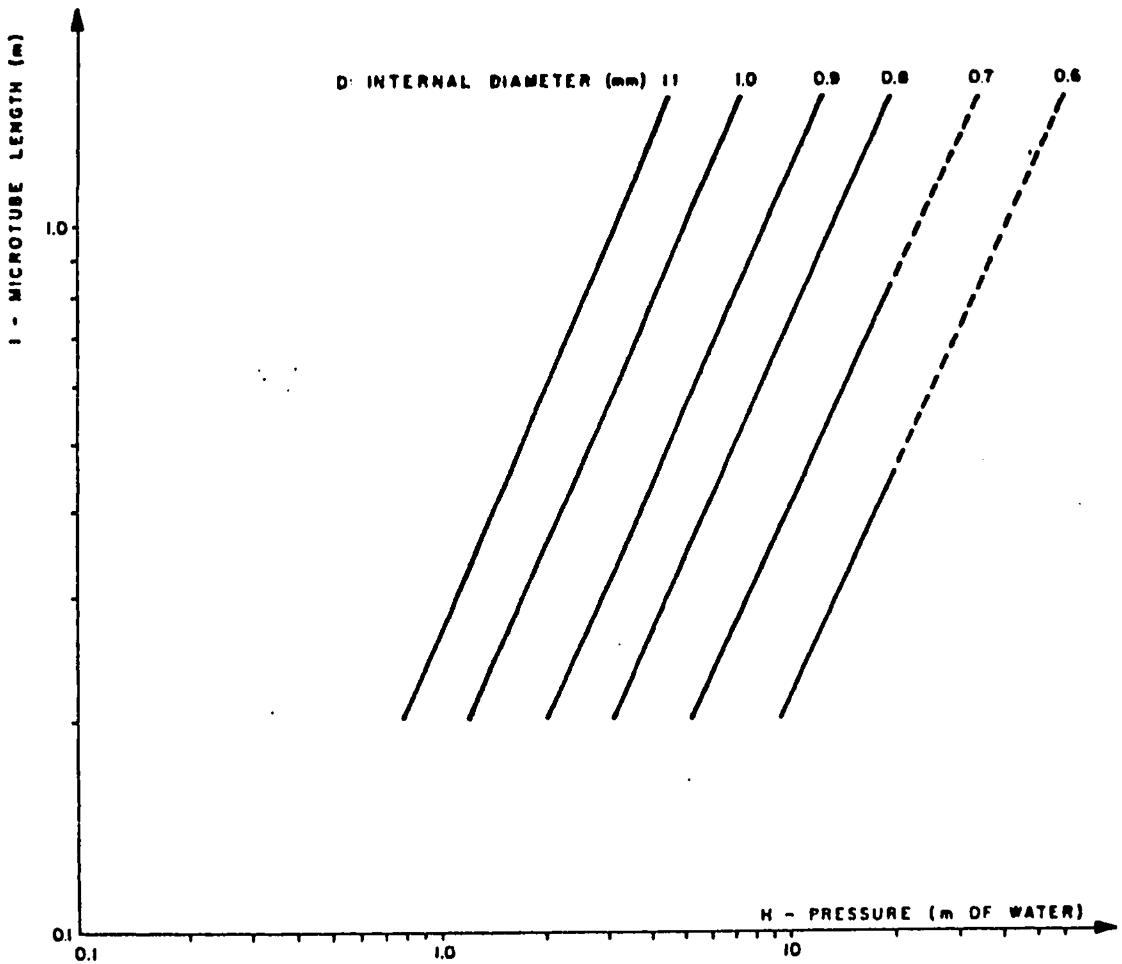


Fig. 30 Microtube q = 4 l/hr. Relation $\ell = f(H)$

Figure (2.4) Microtube design chart by FAO

Based on Christiansen's uniformity coefficient, many design procedures have been developed, e.g. Bin-Ami and Diskin (28), Keller (29), Alperovitz and Shamir (30).

Also based on Christiansen's uniformity coefficient, many design Charts have been developed for lateral design. "Polyplot" was one of the earliest methods that have been developed in Australia for the design of laterals (31).

Wu and Gitlin (32) deviced design Charts that can be used to solve for sloping laterals and submains. Wu also introduced a convenient design calculator, which can be used if the length of the multiple outlet, the discharge, the pressure head and the slope are known.

Karmeli and Peri (33) developed a design procedure for the design of laterals by calculating the pressure head at each outlet backward from the downstream node by subtracting the frictional head loss and the change in elevation from the pressure head of the downstream node.

Roland Perold (34) has developed using pocket calculator an iterative procedure for solving the constant diameter constant slope case. This computer program was developed by means of which the graphical design process for the design of pipe systems can be automated.

Pelban and Amir (35) developed the Lateral Design Procedure (LDP) using a computer program, which calculates four cases differing from

each other by their variables and input. The four cases to be solved by (LDP) are:

1 - discharge and pressure distribution along the lateral;

2 - pressure at inflow node + Case 1;

3 - lateral diameter + Case 2; and

4 - maximum permissible number of outlets on the lateral + Case 2.

LDP Expresses the lateral as a set of non-linear equations to be solved by Newton-Raphson method. This method arrives at the solution by iterations in the following algorithm:

1 - determining an initial approximation of the variable;

2 - correcting the current solution by solving the set of simultaneous linear equations.

The average CPU time for solving the most complicated case by LDP computer program is approximately 1 min. The LDP procedure is limited to a lateral of 30 outlets at the most.

2.3 MAIN AND SUBMAINS

Most trickle irrigation laterals and submains were designed for a single pipe size. The energy gradient line has been derived and presented by an experimental curve that is used as a basis for designing laterals and submains. However, under certain field conditions, the length of laterals and submains may be relatively long and have nonuniform slopes. The relation laterals and submains design

may use a series of different pipe sizes (36,37,38).

Most of the design procedures developed for lateral design were used in the design of main and submains. The designers were using trial and error method to determine the best water profile for the pipe satisfying the design recommendation (4,18).

Wu and Gitlin (39) have shown that a submain can be divided into several sections and varying in sizes. For each section, the energy grade line is very close to a straight line. The study has shown that when the submain is divided into sections, the mean discharge of each can be used to estimate the total energy drop by friction. This characteristic enable the designer to design submain sections by using simple nomograph.

Benami (4) presented an optimum design of a pipe using linear programming. The objective is to minimize the pipe cost and the constraints are to keep the pressure head within certain limits. However, the model minimizes the cost of the single pipe; but it does not consider the optimality of the system as a whole.

Pleban, Shachan and Loftis (18) developed a design procedure using optimization techniques to minimize the capital cost of multi-outlet pipelines which are composed of more than one diameter. The optimization technique suggested is the Lagrange Multipliers method to solve a system of non-linear equations.

CHAPTER (3)

DESIGN OF MICROTUBES

3.1 INTRODUCTION

Microtubes are still widely and satisfactorily used in many countries. They are particularly suitable for undulating and hilly fields, where high variation in heads along the lateral varies according to the difference in elevation (1).

Microtubes may be coiled to increase the head loss, decrease their lengths, and provide better fixation. Microtubes may be coiled around themselves or around the lateral as shown in Figures (3.1 & 3.2) respectively. Microtubes have several advantages which may be summarized as follows:

- They are dramatically less expensive.
- They have the same discharge at all openings along the lateral (if designed properly) even when there is high variation in the operating heads.
- Water quality does not cause clogging or salt accumulation problems as opposed to other emiters.
- They require little maintenance.
- They are simple and flexible which makes it easy to deal with and adopt to different site conditions.

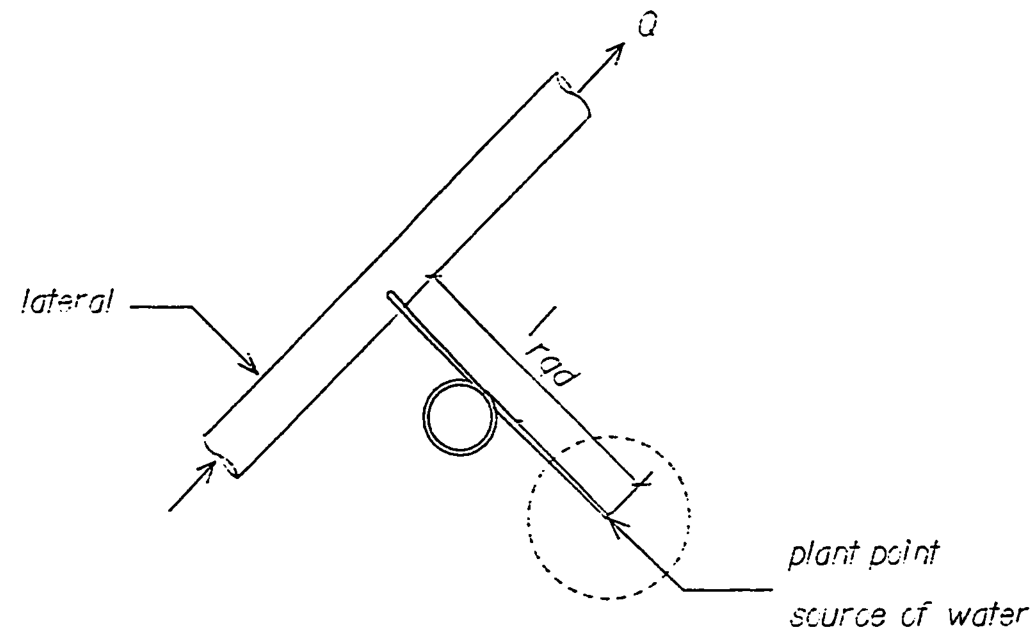


Figure (3.1) Coils Around Themselves

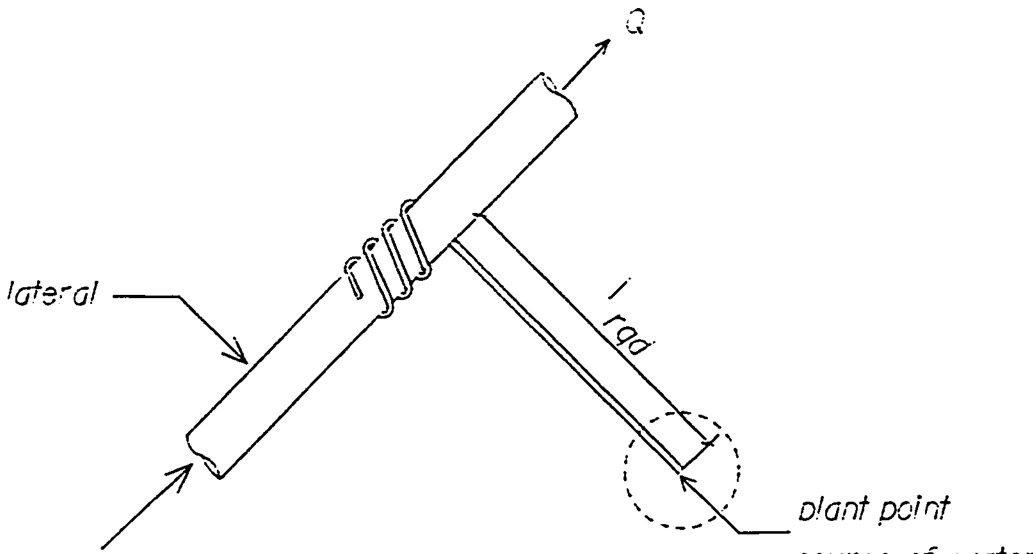


Figure (3.2) Coils Around the Lateral

The discharges through all microtubes are aimed to be equal, but since the operating head at the microtubes inlets are not constant, it is necessary to adjust the lengths to increase the head loss due to friction in order to obtain equal outlet velocity heads (H_V), and hence outlet discharges.

3.2 CHART DEVELOPMENT

The term $\frac{V^2}{2\,g}$, is defined as the velocity head which is expressed by (H_V). Substituting the value (H_V) in Equation (2.3) we get the following equation:

$$H = f \frac{L}{d} H_V \qquad (3.1)$$

The total head and the head losses will be expressed as heads per unit velocity head to build a suitable design Chart. Rearranging Equation (3.1),we will get the following equation:

$$\frac{H}{H_V} = \frac{f}{d} L \qquad (3.2)$$

Denoting $\frac{H}{H_V}$ by (θ), which is the operating total head at the microtube inlet per unit velocity head, Equation (3.2) becomes:

$$\theta = \frac{f}{d} L \qquad (3.3)$$

Equation (3.3) expresses a straight line between (0) and (L) axes, where (f/d) is the slope and it passes through the origin. Figure 3.3 shows the relationship between (0) and (L) for different values of (f/d).

By using the previous hydraulic relationship, one can determine the microtube length for a given total head in the lateral at the microtube inlet, by knowing the following parameters:

a - flow velocity;

b - friction coefficient;

c - microtube diameter; and

d - operating head.

3.3 COMPLIMENTARY CHART DEVELOPMENT

Although the use of the Chart is simple, some additional calculations are needed to determine the value of (f/d) and (0). Therefore, Nomographs are made to obtain (f/d) and (0) without any additional calculations.

3.3.1 Scope of Nomography

A Nomograph, in the simplest and most common form, is a Chart on which one can draw a straight line that intersects three scales in values that satisfy an equation or a given set af conditions (40).

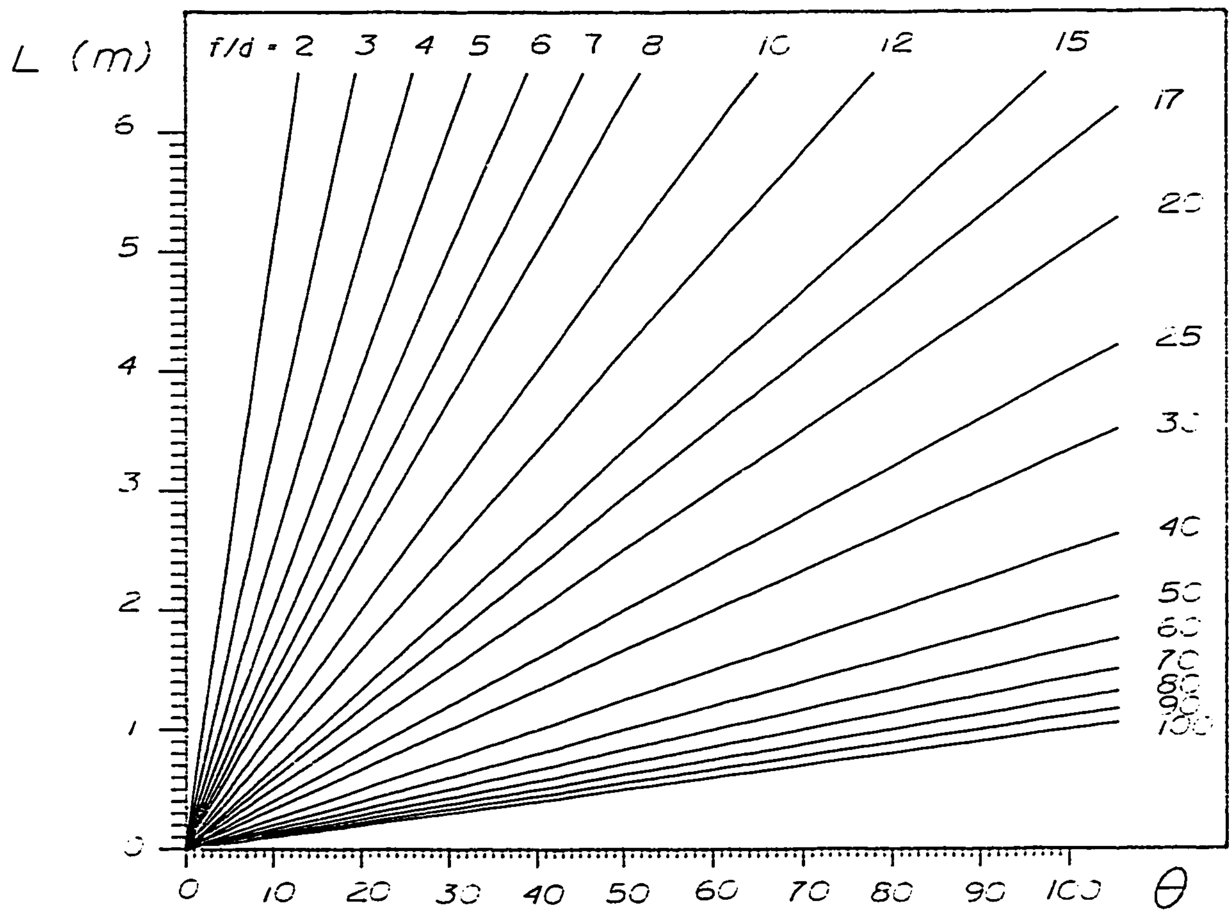


Figure (3.3) Design Chart

"The most frequent scales used are uniform and logarithmic scales. Uniform scales are those on which the spaces between division marks are constant. Logarithmic scales are those on which the spaces between division marks are not constant but vary according to the logarithms of the number that are represented on the scale" (41).

For all scales, the distance is a function of the variable x, which means that scales may express in a form of equations such as:

Uniform	distance = x
Logarithmic	distance = $\log(x)$
Square	distance = x^2
cube	distance = x^3

Figure 3.4 shows different scales on which the distances are proportional to the type of the scale.

"Scale modulus (m) is a factor similar to the "mapping factor" or the scale of a map, which is used to fit the scale with the equation. For example, if a scale in centimeter has to be expressed by X in inches, a scale number (m) of $\frac{1}{2.54}$ fits the actual scale" (40).

$$\text{distance} = \frac{1}{2.54} X$$

Consider the general equation in which one function is equal to the sum of two others,

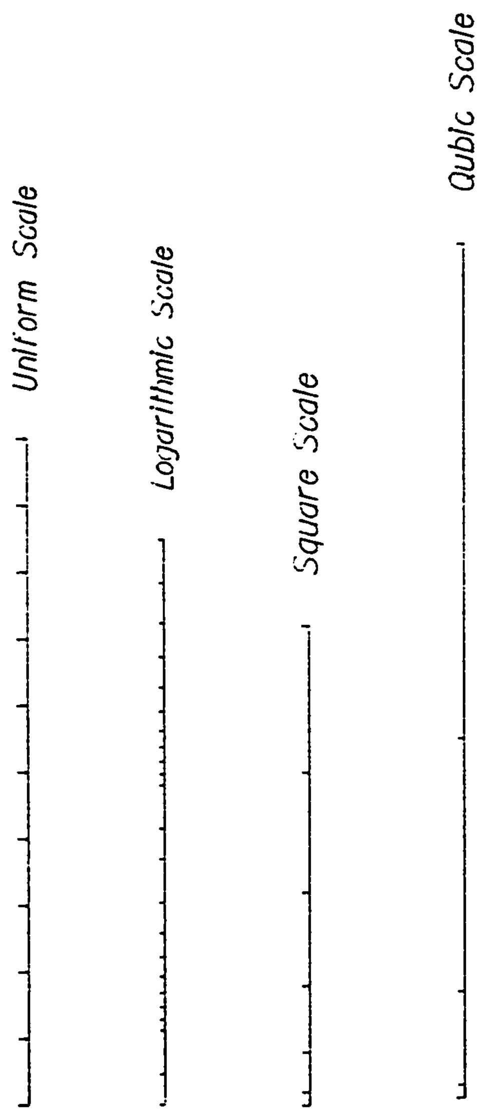


Figure (3.4) Different Scales

$$f_1(u) + f_2(v) = f_3(w)$$

(u) and (v) are plotted with the appropriate scale moduli to make the scales fit the paper as shown in Figure 3.5.

$$u\text{ - scale}: \quad x = m_1 f_1(u)$$

$$v\text{ - scale}: \quad y = m_2 f_2(v)$$

The w-scale will be plotted from

$$z = m_3 f_3(w)$$

where

$$m_3 = \frac{m_1 m_2}{m_1 + m_2} \tag{3.4}$$

Denote the distance between u-scale and w-scale as (a) and denote the distance between v-scale and w-scale as (b)

$$\frac{a}{b} = \frac{m_1}{m_2} \tag{3.5}$$

Multiplication and division problem can be changed to addition and subtraction problems by taking the logarithm, for example;

$$\frac{b\,d^3}{12} = L$$

will be

$$\log b + 3 \log d = \log L + \log 12$$

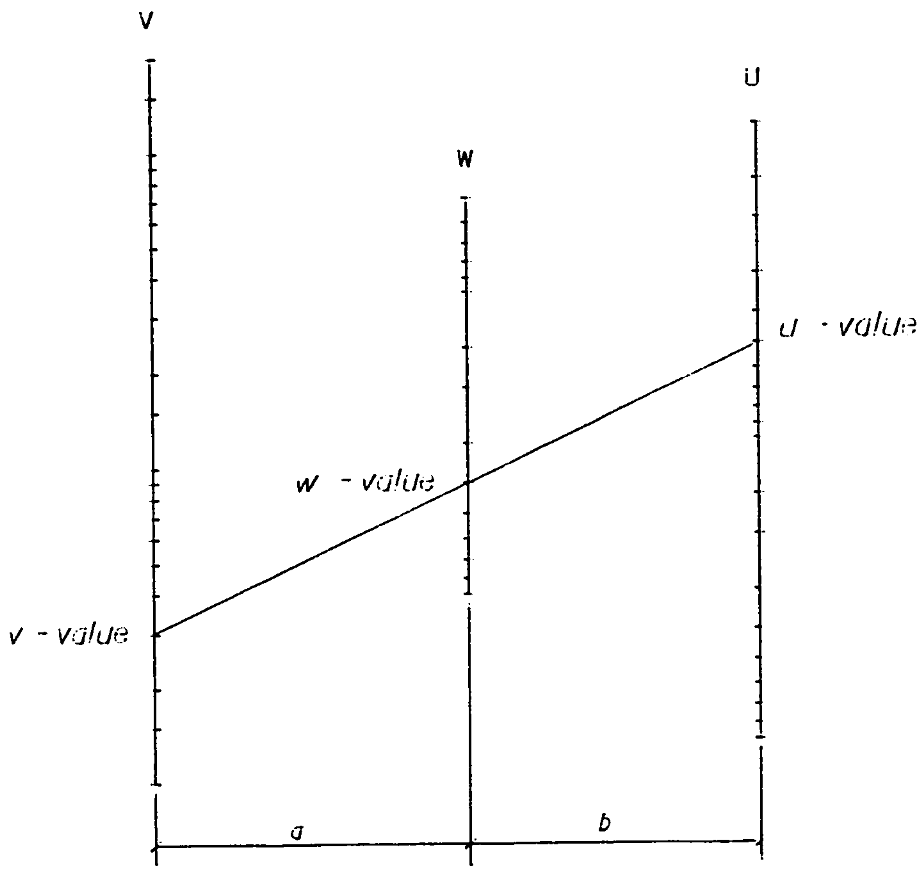


Figure 3.5: Nomograph Notation

3.3.2 The f/d-Nomograph

According to Equations (2.4), (2.5) and (2.6) the outlet discharge (q) and the microtube diameter (d) should be known to determine (f/d). This is however, dependent on the type of the flow (laminar or turbulent) that is governed by Reynolds' number (R).

a - The case of laminar flow (R < 2100)

The Reynolds' number and the friction coefficient in the case of laminar flow were expressed by Equations (2.5) and (2.6) as follows:

$$R = \frac{4\ q}{\pi\ d\ v} \qquad (2.5)$$

$$f = \frac{64}{R} \qquad (2.6)$$

Substitute the value of (R) from Equation (2.5) in Equation (2.6) we get the following equation:

$$f = \frac{64\ \pi\ d\ v}{4\ q} = 50.27\ \frac{d\ v}{q}$$

$$\frac{f}{d} = 50.27\ \frac{v}{q}$$

In metric units $v = 10^{-6}\ \frac{m^2}{s}$ (at a temperature of 20°C)

$$\frac{f}{d} = \frac{50.27 * 10^{-6} * 1000 * 3600\ (l/h)}{q}$$

$$\frac{f}{d} = \frac{180.96}{q} \qquad (3.6)$$

where

q = discharge in (l/h)

d = microtube diameter (m)

(f/d) can be expressed at the same q-Nomograph by dividing 180.96 by (q) Figure 3.6 shows f/d-Nomograph on the same q-Nomograph in the case of laminar flow.

The use of q-scale is limited for laminar flows, where (R) is less than 2100. The critical discharge (q_c) corresponding to a value of (R) equals to 2100 should be determined for different microtube diameters. These values of q_c are the maximum limits for using q-scale to determine (f/d) for laminar flow.

Equation (2.5) could be reformulated as follows

$$q = \frac{R}{4} \pi d v$$

At the critical discharge (q_c), the value of the Reynolds' number will be equal to 2100 and v equals to 10^{-6} m^2/s at 20°C.

$$q_c = \frac{2100}{4} \pi d v$$

$$v = 10^{-6} \ m^2/s$$

$$q_c = \frac{2100}{4} * \pi * d * 10^{-6} * \frac{1000 * 3600 \ (l/h)}{1000 \ (mm)}$$

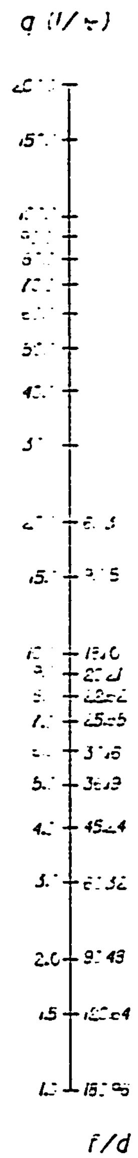


Figure (3.6) f/d in Case of Laminar Flow

$$q_c = 5.938\ d \tag{3.7}$$

where

q_c = discharge in (l/h)

d = microtube diameter (mm)

The critical values of discharge for different microtube diameters are shown in Table 3.1.

diameter (mm)	discharge (l/h)
4.0	23.75
3.0	17.81
2.5	14.84
2.0	11.88
1.5	8.91
1.0	5.94
0.6	3.56

Table 3.1 Critical Values of Discharges for Different Microtube Diameters.

b - The case of turbulent flow (R > 2100)

The Reynolds' number and the friction coefficient in the case of turbulent flow were expressed earlier by Equations (2.4) and (2.5) as follows:

$$f = \frac{0.316}{R^{0.25}} \tag{2.4}$$

$$R = \frac{4\ q}{\pi\ d\ \nu} \tag{2.5}$$

$$R = \frac{4 * q\ (l/h)}{\pi\ d\ (m) * 10^{-6} * 1000 * 3600}$$

$$R = 0.354\ \frac{q\ (l/h)}{d\ (m)} \tag{3.8}$$

Substitute the value of the Reynolds' number (R) from Equation (3.8) in Equation (2.3)

$$f = \frac{0.316}{(0.354\frac{q}{d})^{0.25}}$$

$$f = \frac{0.41\ d^{0.25}\ (m)}{q^{0.25}\ (l/h)} \tag{3.9}$$

$$\frac{f}{d} = \frac{0.41}{d^{0.75} q^{0.25}} \tag{3.10}$$

Taking the logarithm and multiply by minus sign both sides of Equation (3.10)

$$-\log \frac{f}{d} = 0.75 \log d + 0.25 \log q + 0.387 \tag{3.11}$$

Assume $0.25\ m_1 = 8$

$$m_1 = 32$$

Assume $0.75\ m_2 = 8$

$$m_2 = 10.67$$

$$m_3 = \frac{32 * 10.67}{32 + 10.67} = 8$$

Assume the distance between q-Nomograph and d-Nomograph equals to 8 cm, the distance between q-Nomograph and f/d-Nomograph is (a) and the distance between f/d-Nomograph and d-Nomograph is (b).

$$a = \frac{32}{32 + 10.67} * 8 = 6 \text{ cm}$$

$$b = \frac{10.67}{32 + 10.67} * 8 = 2 \text{ cm}$$

Figure 3.7 shows f/d-Nomograph in case of laminar and turbulent flows.

Note : Although the values of the microtube diameters are expressed in meters, it is better to express them in millimeters on the d-Nomograph for easier use.

3.3.3 The V-Nomograph

The velocity of flow (v) can be expressed as a function of the discharge (q) and the microtube diameter (d). This relation can be formulated as follows:

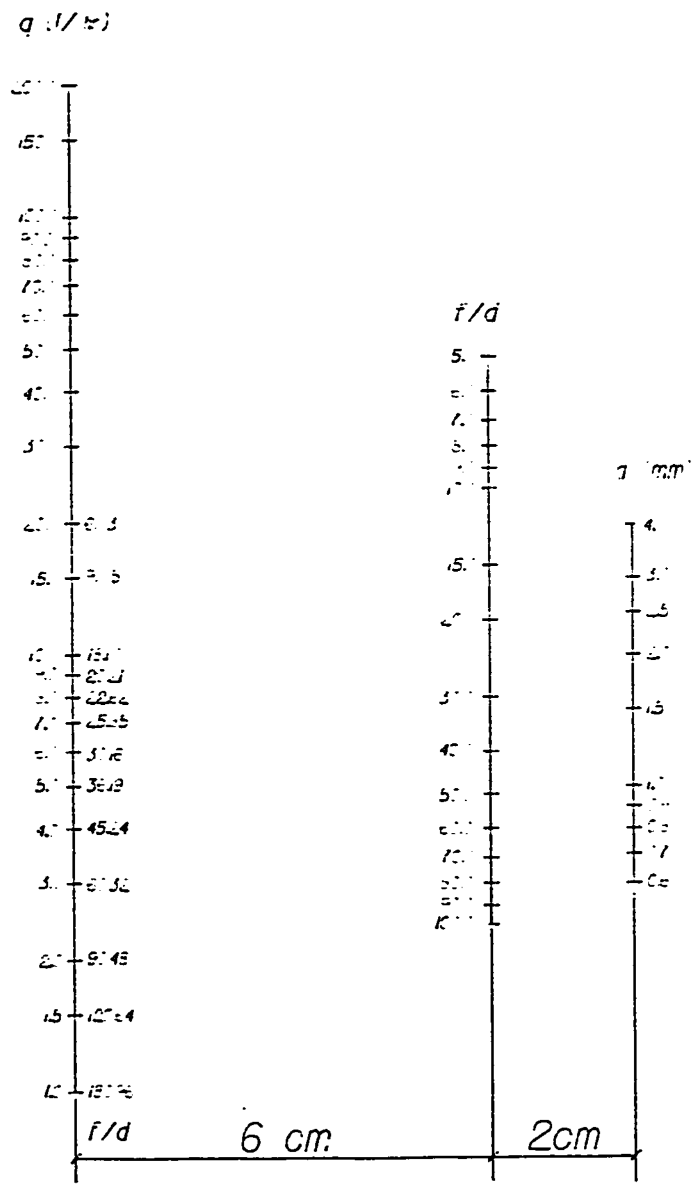


Figure (3.7) f/d - Nomograph

$$v = \frac{4\ q}{\pi\ d^2} \qquad (3.12)$$

$$v = \frac{4\ q\ (l/h)}{\pi\ d^2 * 1000 * 3600\ (m)}$$

$$v = \frac{0.354\ q\ (l/h)}{d^2\ (mm)} \qquad (3.13)$$

Taking the logarithm for both sides of Equation (3.13)

$$\log v = \log 3.54 * 10^{-7} + \log q - 2 \log d$$

$$\log d = -\ 6.451 + \frac{1}{2} \log q - \frac{1}{2} \log v \qquad (3.14)$$

for d - scale : $m_3 = 8$

for q - scale : $m_1 * \frac{1}{2} = 8$

$$m_1 = 16$$

$$\frac{16 * m_2}{16 + m_2} = 8$$

$m_2 = 16$ (for v-Nomograph)

Assume the distance between v-Nomograph and d-Nomograph is (b). The distance (a) between q-Nomograph and d-Nomograph has been determined before equals 8 cm.

$$b = \frac{m_2 * a}{m_1}$$

$$b = \frac{16 * 8}{16} = 8 \text{ cm}$$

Figure 3.8 shows v-Nomograph combined with q-Nomograph and d-Nomograph.

3.3.4 The (θ)-Nomograph

The operating head per unit velocity head (θ) has been defined earlier as $\frac{2\,g\,H}{v^2}$.

$$\theta = \frac{2\,g\,H}{v^2}$$

$$\log \theta = \log 2\,g + \log H - 2 \log v$$

$$\log \theta = 1.293 + \log H - 2 \log v \qquad (3.15)$$

For v-Nomograph: $2\,m_1 = \frac{1}{2} * 16$

$$m_1 = 4$$

Assume $m_2 = 14$ (for H-Nomograph)

$$m_3 = \frac{14 * 4}{14 + 4} = 3.11$$

Assuming the distance between θ - Nomograph and v-Nomograph equals to 2 cm and the distance between H-Nomograph and v-Nomograph is (x)

$$\frac{2}{m_1} = \frac{x}{m_2}$$

$$\frac{2}{14} = \frac{x}{4}$$

$$x = 7.00 \text{ cm}$$

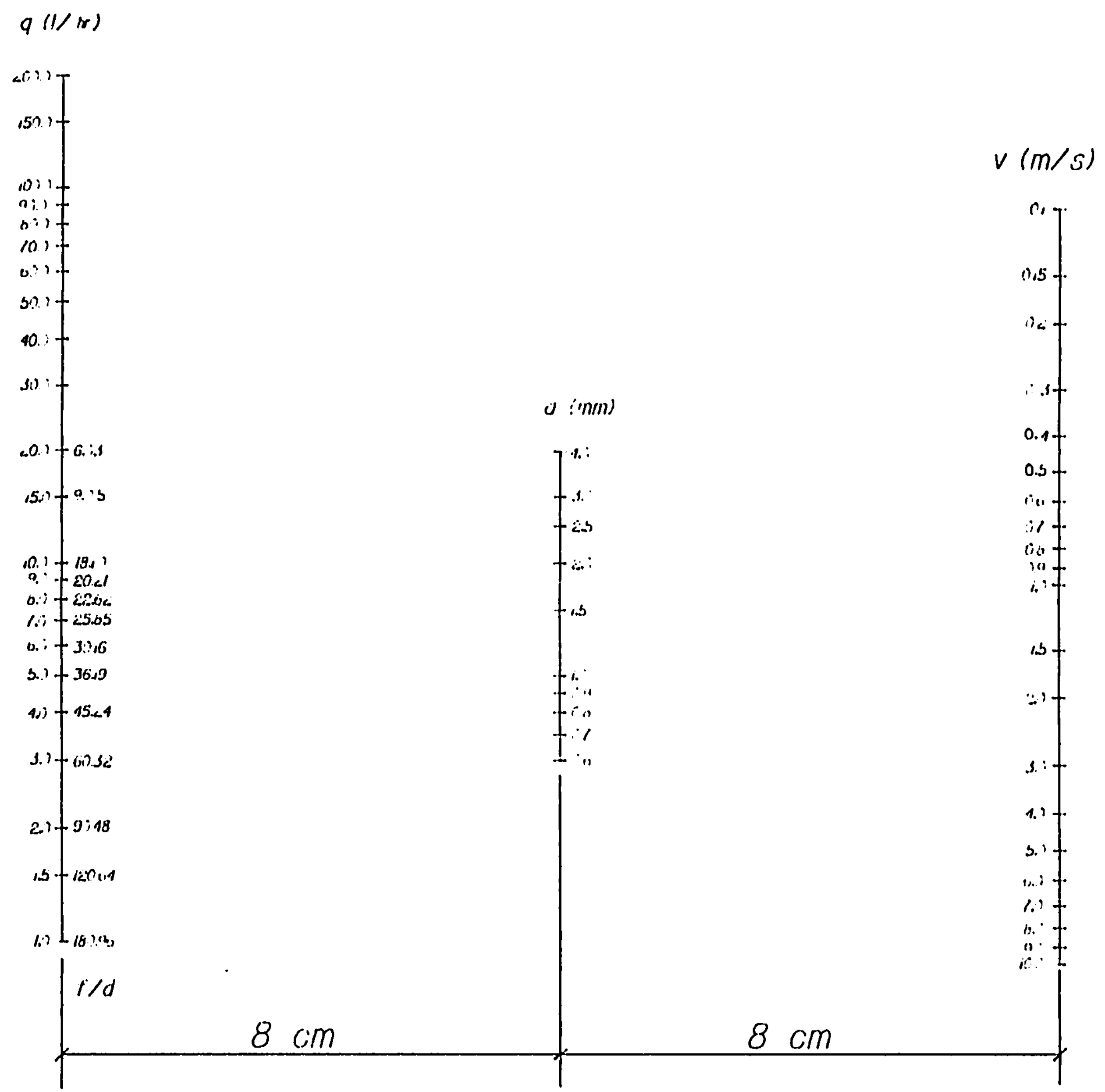


Figure (3.8) V - Nomograph

Therefore the distance between H-Nomograph and v-Nomograph equals to 7.00 cm.

Figure 3.9 shows θ -Nomograph combined with q-Nomograph and H-Nomograph.

3.3.5 Temperature Variation

FAO (1) published a Table representing the effect of temperature on the microtube discharge. Table (3.2) shows this Table, where correction factors should be multiplied by the designed discharge to determine the actual discharges at different temperatures.

A temperature of (20^{0}C) was chosen as a design temperature in the development of the design Chart and Nomographs. If the actual site temperature is different than (20^{0}C) the required discharge should be divided by a correction factor from Table (3.2). A new discharge will be obtained to be used in the design Nomographs to get the required actual discharge.

3.4 NOMOGRAPHS DEVELOPMENT

The required values of $\frac{f}{d}$ and (θ) can be determined by using the previous Nomographs. Collecting the Nomographs in one Chart will make the determination much easier.

D (mm)	20°C	30°C	40°C	50°C
0.5	100	110	120	125
0.6	100	108	115	122
0.7	100	106	112	117
0.8	100	105	110	115
0.9	100	104	108	112
1.0	100	104	107	111
1.1	100	104	107	110

Table (3.2) Temperature Correction Factor by FAO

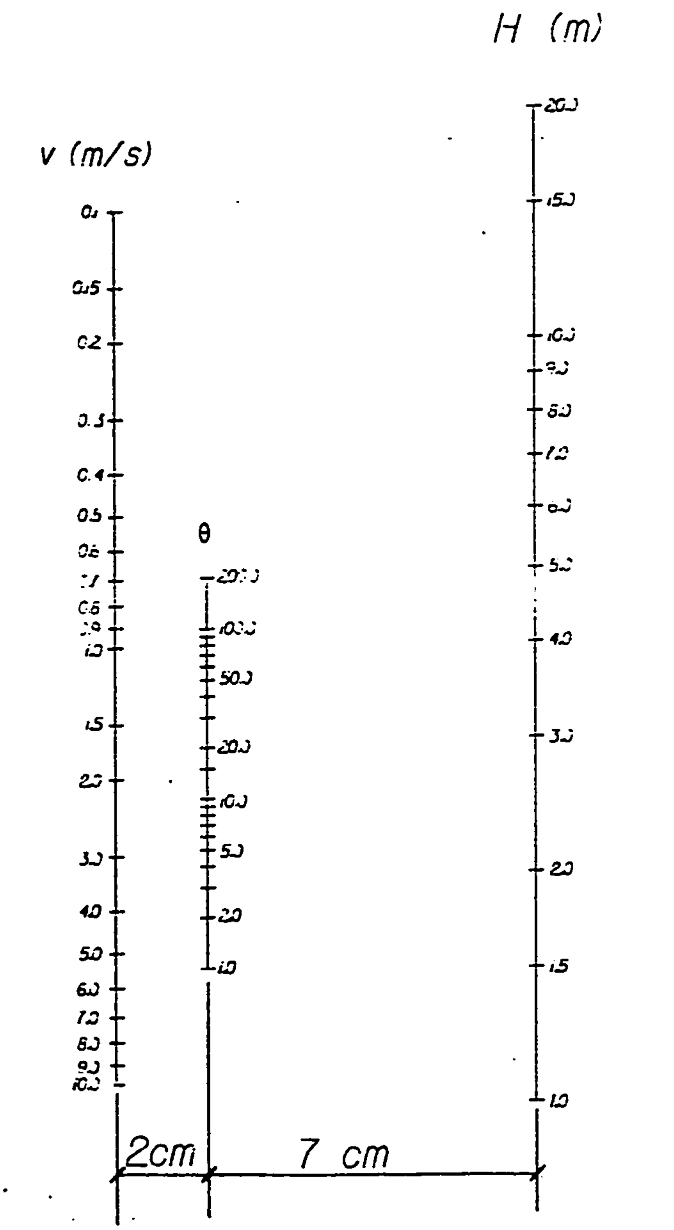


Figure (3.9) θ - Nomograph

Figure 3.10 shows the design Nomographs, which can be used directly by the designer.

3.5 MICROTUBE LENGTHS DETERMINATION USING THE CHART AND NOMOGRAPHS

Before determining the microtube lengths using the Chart and Nomographs the following must be specified:

a - operating head in the lateral at the microtube inlet;

b - required discharge; and

c - microtube diameter.

The design steps to determine the microtube length are as follows:

- Draw a line connecting the value of microtube diameter (d) and the value of microtube discharge (q), the intersection of this line with f/d-Nomograph determines the value of (f/d). The value of (f/d) is constant for all microtubes, since they provide equal amount of discharge and have the same diameter. (f/d) point is considered a **reference point** for all microtubes.
- In the case of laminar the value of (f/d) is determined on the q-Nomograph and moved to the f/d-Nomograph as the reference point.
- The line connecting (q) and (d) is extended to intercept the v-Nomograph to determine the value of the flow velocity, which is also fixed and considered as another reference point for all microtubes.
- The value of (θ) is determined on the θ - Nomograph by intersecting the line connecting the flow velocity (v) (reference point) and the

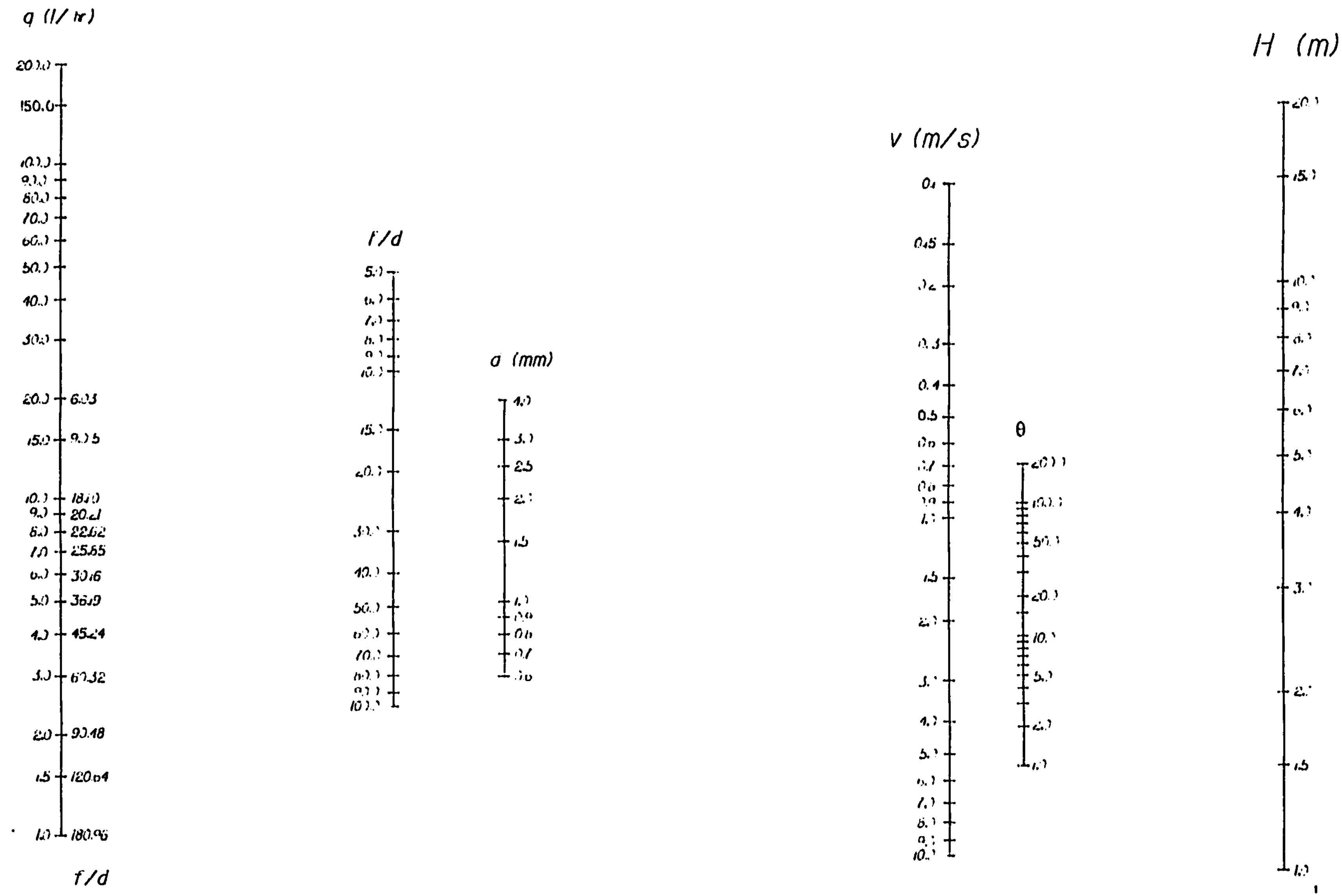


Figure (3.10) Dessign Nomographs

operating head (H) with θ - Nomograph.

- Move the value of (θ) and (f/d) obtained from the Nomographs in the Chart.
- From the value of (θ) on the θ - axis a vertical line is drawn to intercept the straight line of (f/d). Interpolation may be used for intermediate values.
- From the interception of the vertical line drawn from (θ) and the line of (f/d), a horizontal line is drawn to intercept the vertical axis (L) at a point, which is the required microtube length.
- The procedure is repeated for all microtubes throughout the network, which begins with the reference point (v) in the Nomographs. The values of the heads in the lateral at the microtubes inlets (H) are introduced in the Nomographs to determine their corresponding (θ) values. The values of (θ) are moved to the design Chart to determine the microtube length corresponding to each (θ) value.

Figures (3.11a & 3.11b) show the microtube design steps using the Nomographs and Chart.

3.6 MODIFIED DESIGN CHART

Many head losses, which have not been taken into account in the Chart development, may act on the system. Example of such head losses is the head loss due to coiling of microtubes. The developed design Chart has the capability to incorporate any additional head loss in the design. Each head loss should be formulated as a head per unit

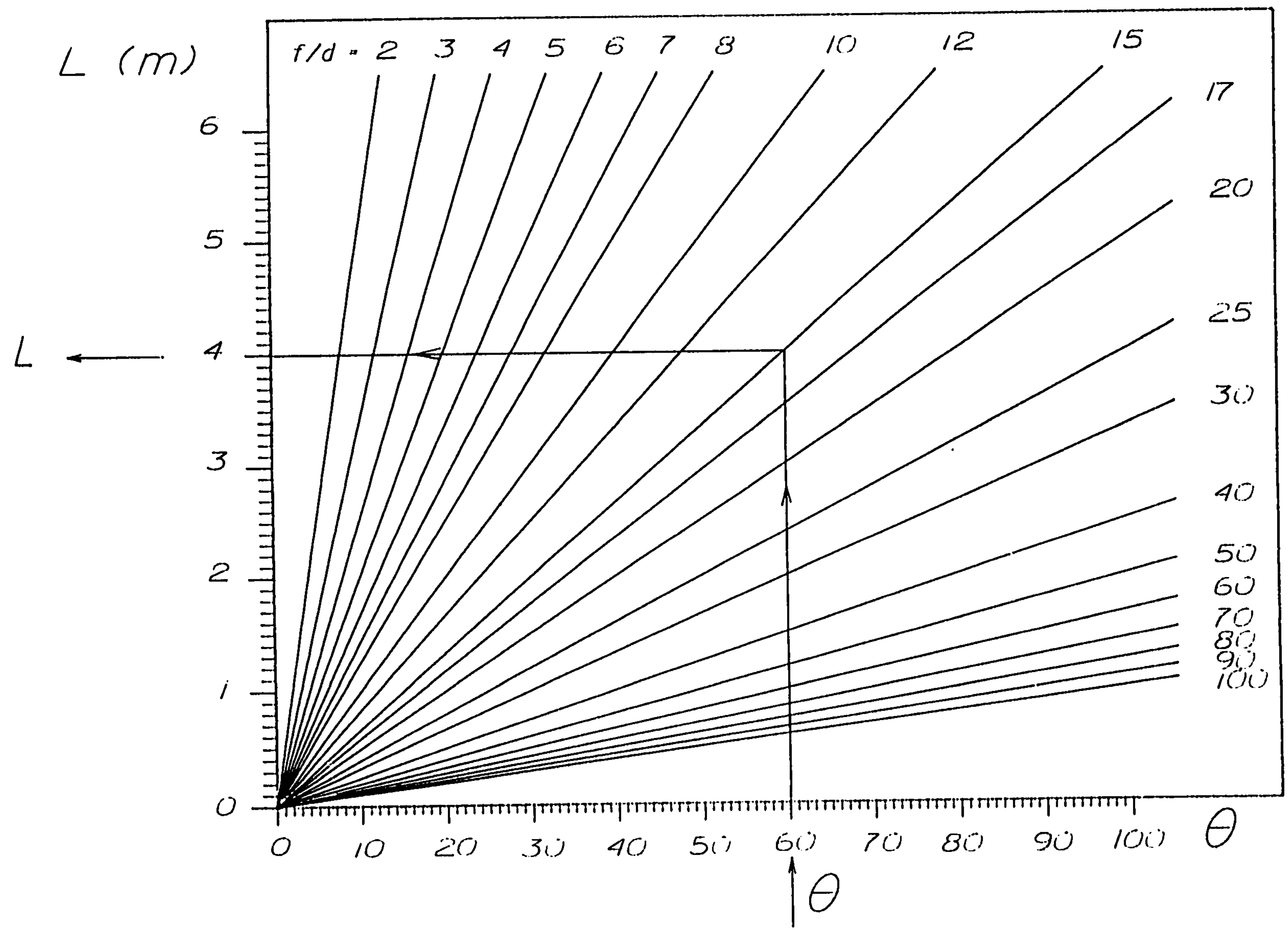


Figure (3.11.a) Design Chart Steps

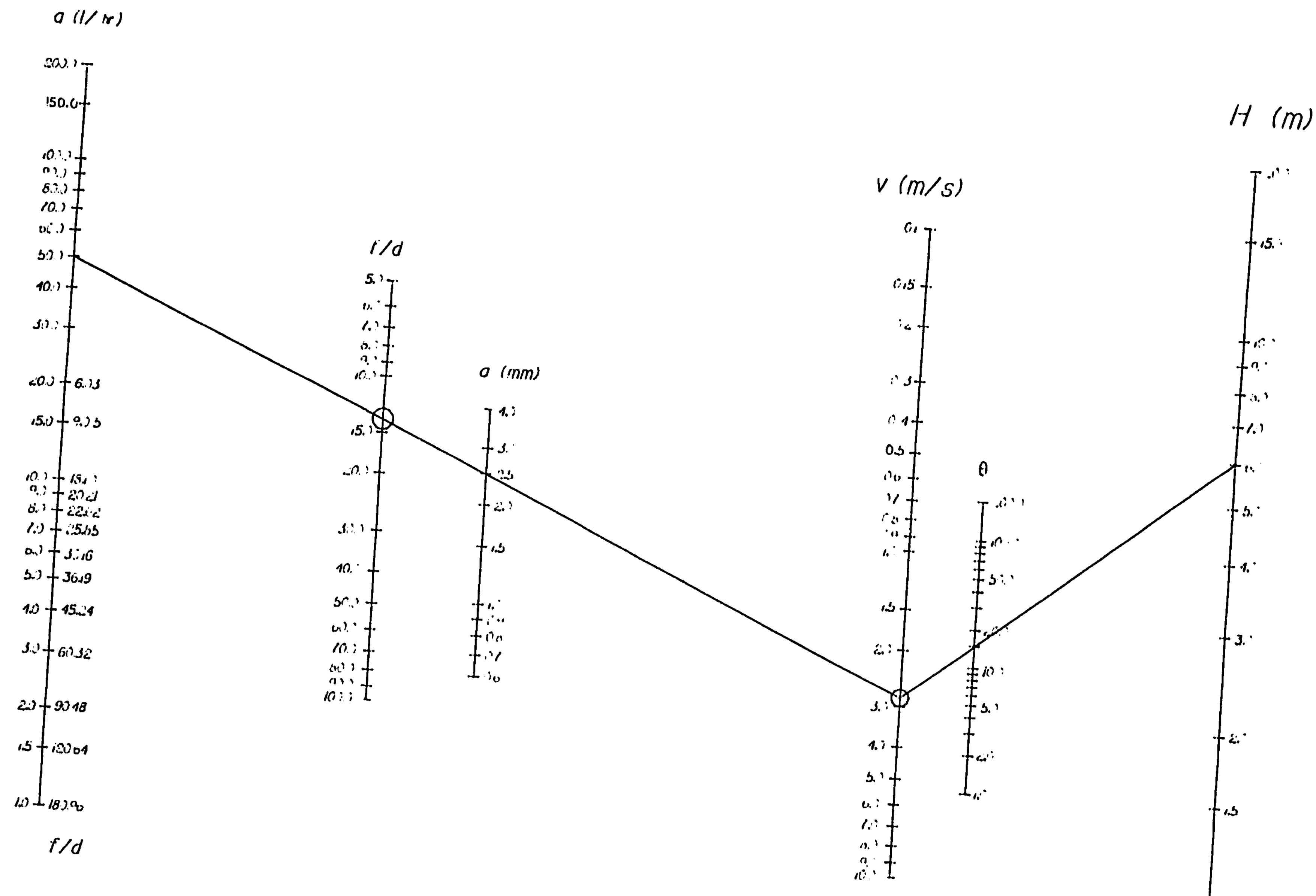


Figure (3.II.b) Nomograph Design Steps

velocity head which, in turn, should be subtracted from the operating total head per unit velocity head (0). In the following sections, the required microtube length (l_{rqd}) and the coil loss will be introduced in the design Chart. However, the door is opened for any other head loss to be added to the Chart in the form of head per unit velocity head.

3.6.1 Required Microtube Length (l_{rqd})

The required microtube length (l_{rqd}) is the distance between the lateral and the plant, where the calculated microtube length should be greater than or equal to that length. The required microtube length (l_{rqd}) is a design recommendation given by the designer.

The total microtube length (L) consists of the required microtube length (l_{rqd}) and the coiled length (l_{co}). The separation between the coiled length (l_{co}) and the required microtube length (l_{rqd}) is essential in the case of using coils. This is because only the coiled length (l_{co}) will provide extra head loss. Figures 3.1 and 3.2 shows the required microtube length when coils are around the lateral or around themselves.

The required microtube length (l_{rqd}) can be included in Equation (3.3) by setting

$$L = l_{co} + l_{rqd} \qquad (3.16)$$

Substitute the value of (L) from Equation (3.16) in Equation (3.3) we get the following equation:

$$\theta = \frac{f}{d} (l_{co} + l_{rqd})$$

$$\theta - \frac{f}{d} l_{rqd} = \frac{f}{d} l_{co} \qquad (3.17)$$

To determine the coiled length (l_{co}), a value of $\frac{f}{d} l_{rqd}$ should be subtracted from (θ) value to obtain a modified (θ) value. (An easy way to determine the modified (θ) value will be provided later). Based on the modified (θ), the coiled length (l_{co}) can be determined from the Chart.

Denoting the value of ($\frac{f}{d} l_{rqd}$) as (γ'), a Nomograph will be developed to determine the value of (γ') to obtain a modified (θ) value.

3.6.2 The γ '-Nomograph

Knowing (l_{rqd}) and ($\frac{f}{d}$), the value of (γ') can be determined from the following simple equation

$$\gamma' = \frac{f}{d} * l_{rqd}$$

$$\log \gamma' = \log \frac{f}{d} + \log l_{rqd} \qquad (3.18)$$

Since the logarithmic f/d-Nomograph has been developed earlier, the

logarithmic l_{rqd} - Nomograph is needed to be developed with appropriate scale. The scale modulus (m_1) for f/d-Nomograph has been determined before equals 8. Assume m_2 equals to 6 (for f/d-Nomograph

$$m_3 = \frac{6 * 8}{6 + 8} = 3.4286$$

Assume the distance between f/d-Nomograph and l_{rqd} - Nomograph equals to 8 cm, the distance between γ' - Nomograph and l_{rqd} - Nomograph is (a) and the distance between γ' - Nomograph and f/d-Nomograph ' is (b);

$$a = \frac{m_2 * 8}{(a + b)} = \frac{6 * 8}{(6 + 8)} = 3.4286 \text{ cm}$$

$$b = 8 - 3.4286 = 4.5714 \text{ cm}$$

Figure 3.12 shows γ' - Nomograph combined with l_{rqd} - Nomograph and f/d-Nomograph.

3.6.3 Microtube Length - Number of Coils Relationship

The number of coils (N_L) can be expressed in terms of the coiled length (l_{co}) The relation between the coiled length and the number of coils is as follows:

$$N_L = \frac{l_{co}}{\pi D_{co}} \qquad (3.19)$$

where

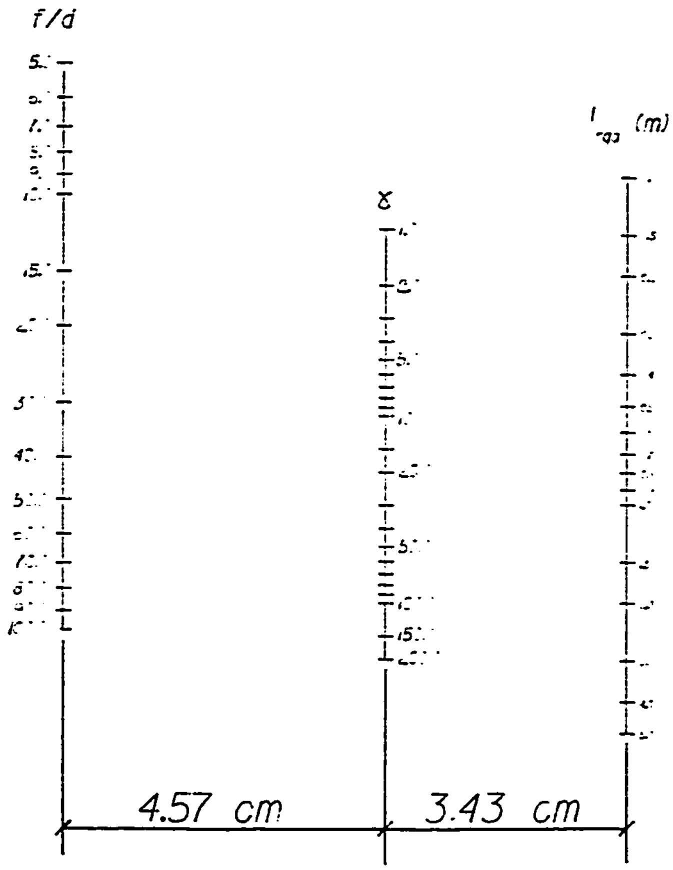


Figure (3.12) γ - Nomograph

N_L = number of coils

D_{co} = diameter of the coil

the equation can be reformulated as

$$l_{co} = \pi D_{co} N_L \tag{3.20}$$

The relation between the microtube length and the number of coils is a straight line with a slope of (πD_{co}) and passing through the origin. A group of straight lines for different values of coil's diameters are drawn to determine the number of coils for a given coil length and diameter. These straight lines are shown in Figure 3.13. Interpolation may be used for intermediate values of coil diameters.

3.6.4 Head Loss Due to Coiling - Number of Coils Relationship

The head loss through a bend has been formulated as a constant (k) multiplied by the velocity head. The constant (k) can be computed by the following equation developed by Hinds (27).

$$k = \left(0.13 + 1.85 \left(\frac{d}{D_{co}}\right)^{3.5} \right) \sqrt{\frac{\alpha}{180}} \tag{3.21}$$

where

α = bend angle

In the case of a complete coil, the bend angle (α) will be equal to 360^0 Considering the extreme case when the diameter of the microtube

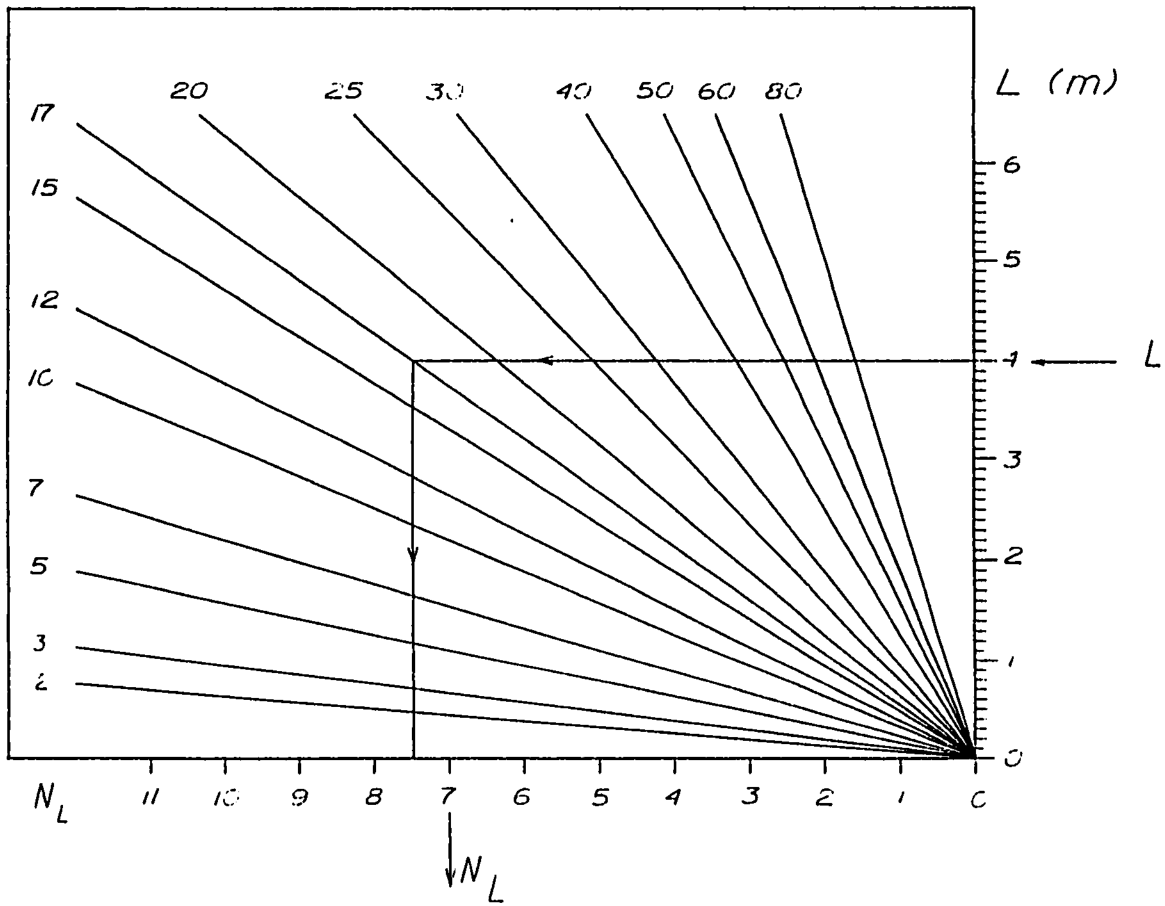


Figure (3.13) Microtube Length - Number of Coils Relationship

is a maximum (4 mm) and the diameter of the coil is a minimum (20 mm), only a fraction equals 0.0035 will be added to 0.13 within the brackets. This will increase the (k) value by 5% .Thus for all practical purposes the value of $\left(\frac{d}{D_{co}} \right)^{3.5}$ may be deleted from Equation (3.21).

Equation (3.21) is reformulated in the case of coiled microtubes as:

$$k = (0.13)\sqrt{\frac{360}{180}} = 0.184 \qquad (3.22)$$

The head loss due to coiling (H_{co}) of (N_L) number of coils can be expressed as:

$$H_{co} = 0.184\, N_L \frac{V^2}{2\,g} \qquad (3.23)$$

Substitute the value of $\frac{V^2}{2\,g}$ by (H_V), therefore Equation (3.23) can be rearranged as:

$$N_L = 5.44 \frac{H_{co}}{H_V} \qquad (3.24)$$

Denote $\frac{H_{co}}{H_V}$ as (γ), the relation between (γ) and (N_L) is a straight line with 5.44 slope and passing through the origin. Figure 3.14 shows the relationship between (γ) and (N_L).

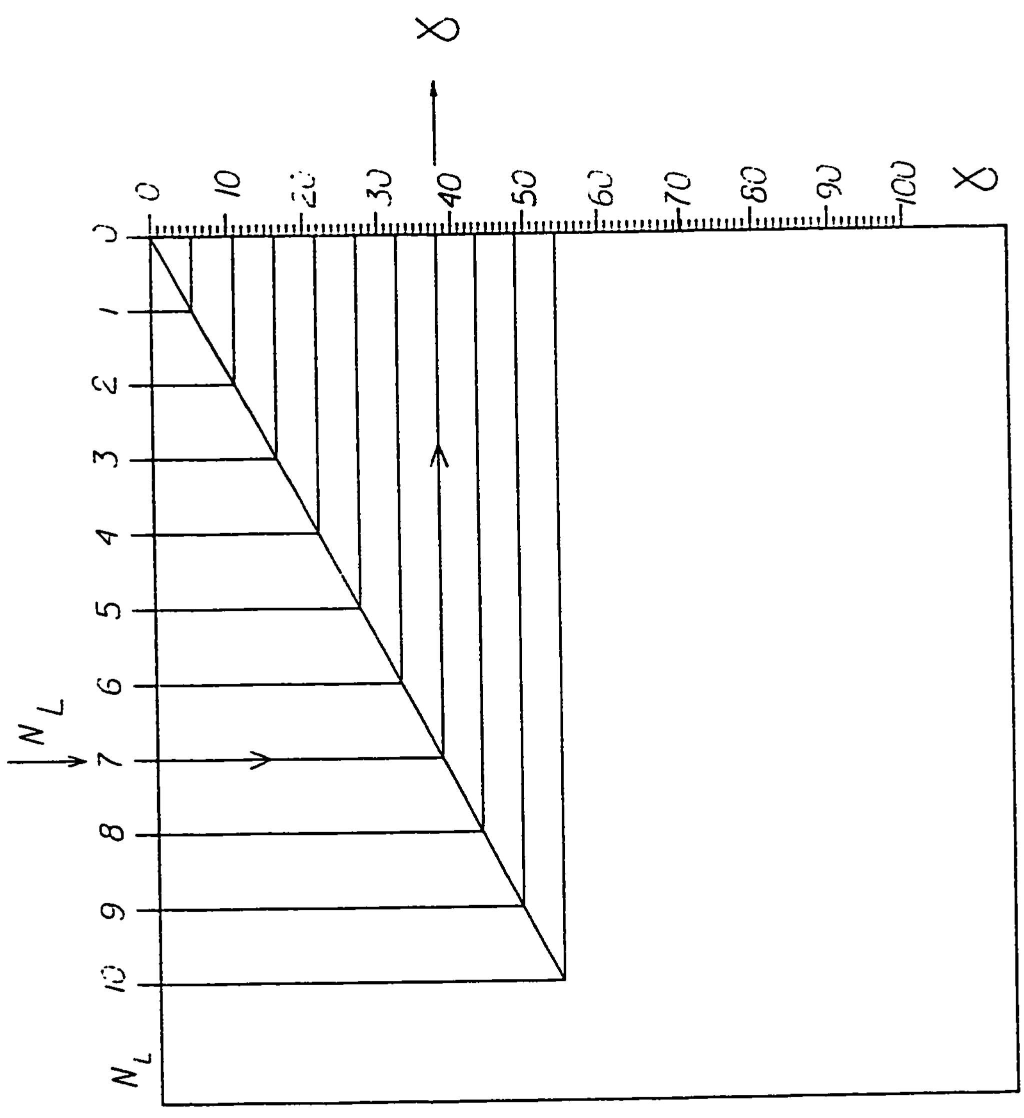


Figure (3.14) Number of Coils - Head Loss Relationship

3.6.5 The ($\gamma - \theta$) Relationship

Coil head loss per unit velocity head (γ) can be introduced into the Chart by drawing a group of lines incline at an angle of 45^0 drawn between two perpendicular (θ) and γ-axes. The value of (γ) can be subtracted from (θ) by reflecting its value on the incline 45^0 line coming from (θ) and project the point of intersection on the 0 - axis to obtain the value of ($\theta - \gamma$). Figure 3.15 shows $0 - \gamma$ relationship.

3.7 MODIFIED CHART AND NOMOGRAPHS DEVELOPMENT

The head loss due to coiling will be introduced in the Chart by adding the following relationships

a - Microtube lengths and the number of coils

b - Number of coils and head loss due coiling per unit velocity head

c - Head loss due to coiling per unit velocity head and the acting head per unit velocity head

The modified Chart can be built up by linking the above relationships, such a Chart further linked to (θ) vs (L) relationship as shown in Figure 3.16.

Also (I_{rqd}) - Nomograph and γ - Nomograph will be added into the previously developed Nomographs to make modified Nomographs as shown in Figure 3.17.

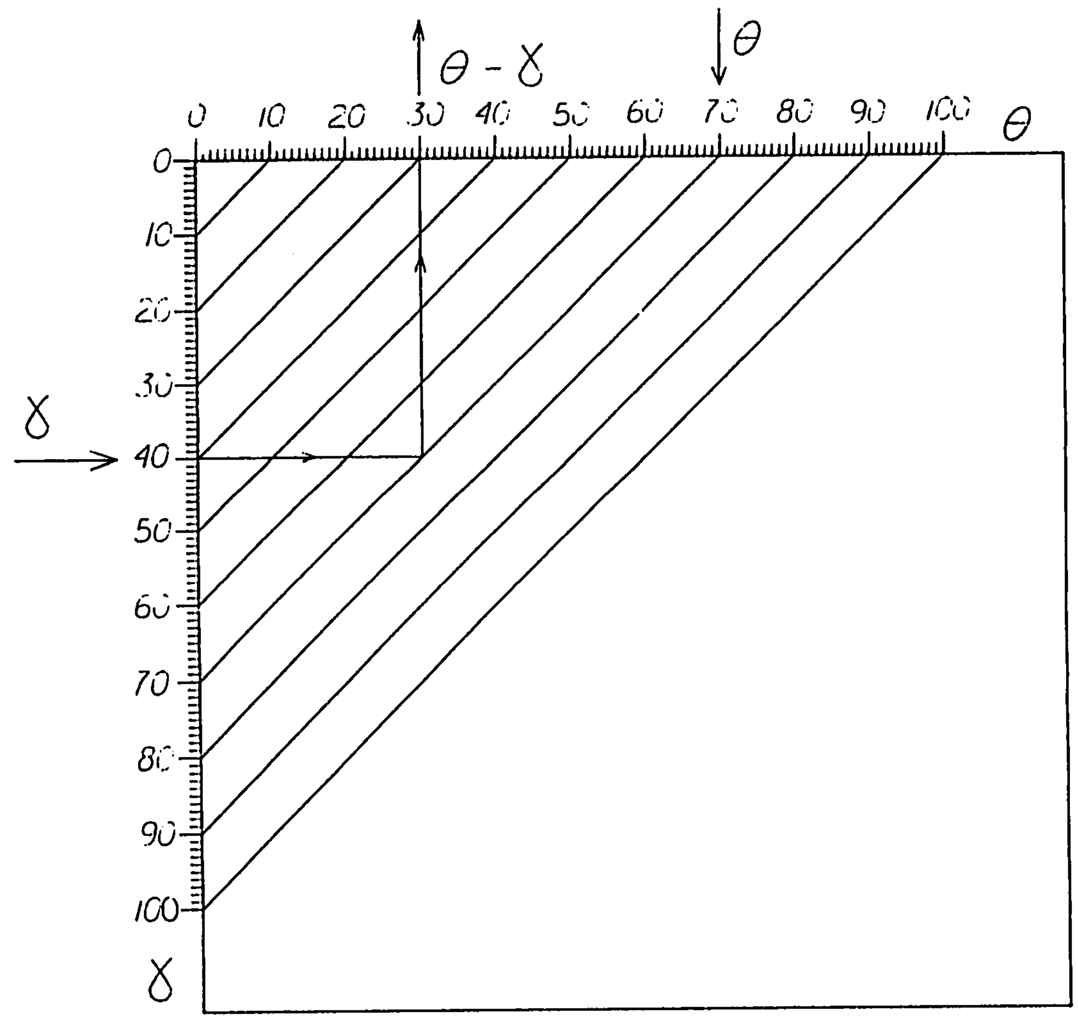


Figure (3.15) Head Loss - Operating Head Relationship

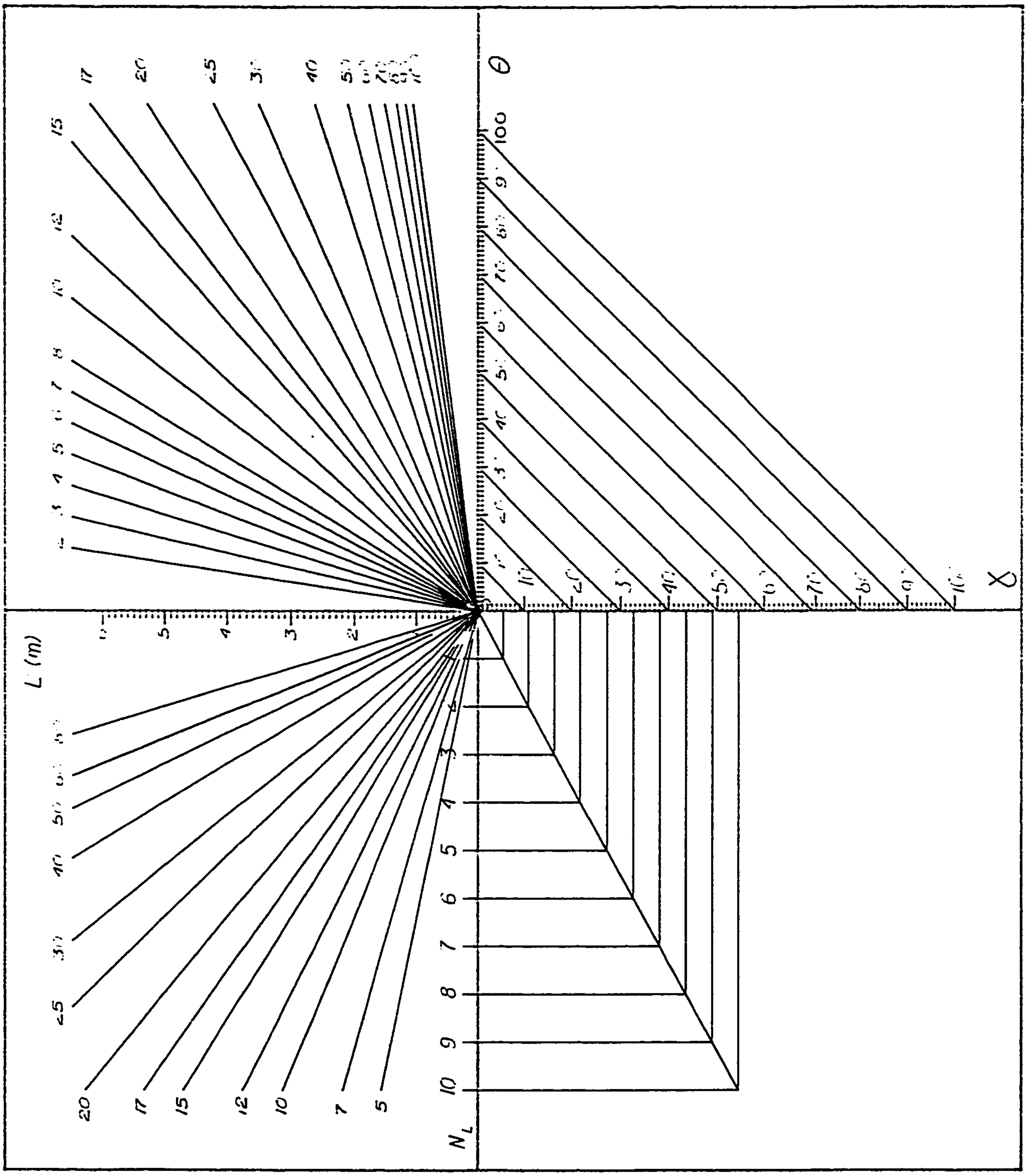


Figure (3.16) Modified Design Chart

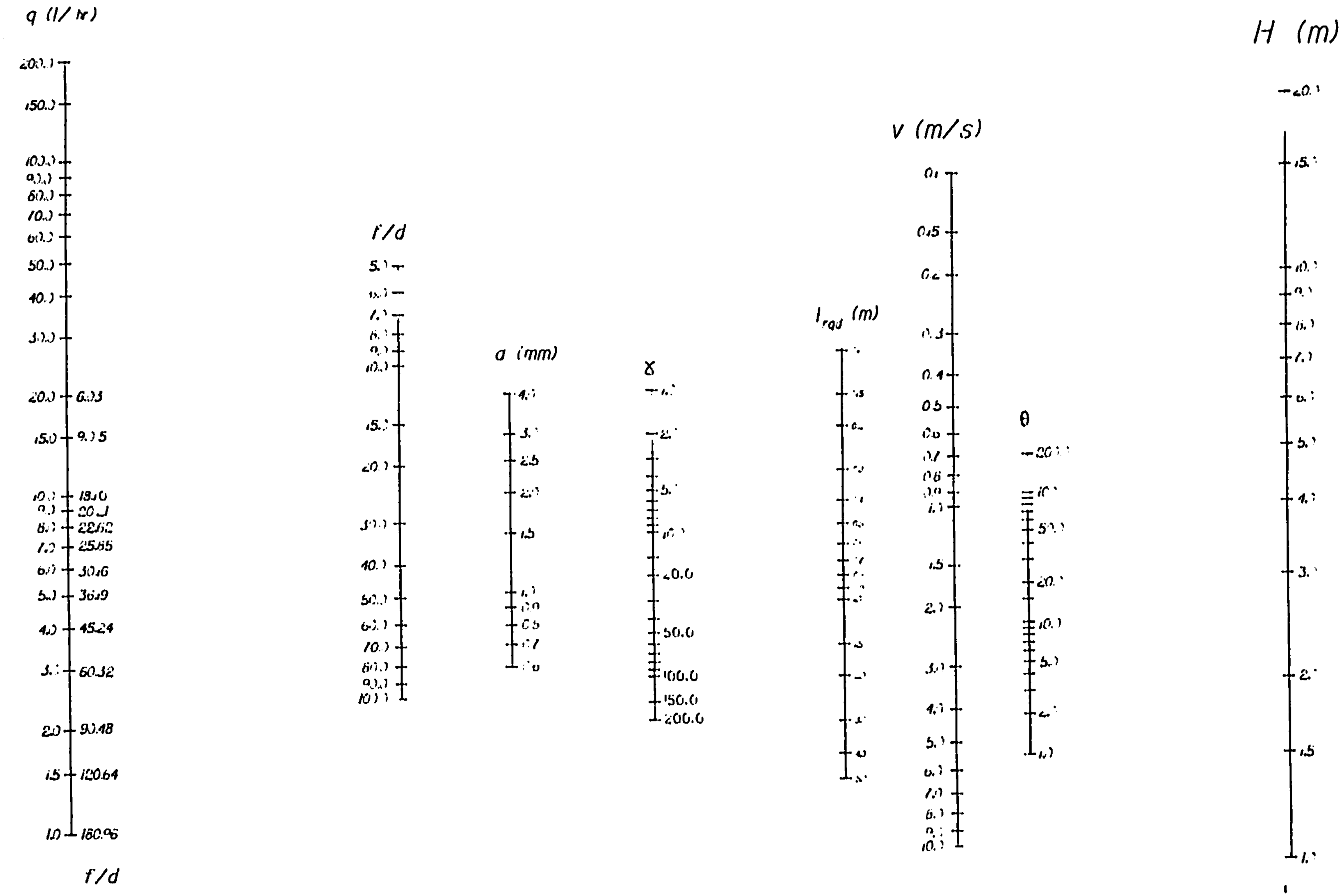


Figure (3.17) Modified Design Nomographs

3.8 MICROTUBE LENGTHS USING THE MODIFIED DESIGN CHART AND NOMOGRAPHS

The following steps should be adopted to use the modified Chart and Nomographs

- First step is to determine the values of (f/d), (γ') and (θ) from the Nomographs as described earlier.
- Subtract the value of (γ') from (θ) by substituting the value of (γ') on the γ-**axis** and 'reflect its value on the incline 45^0 line obtained from (θ) value and projected it on the θ-**axis** to obtain a modified (θ).
- The microtube length corresponding to the modified (θ) could be determined as shown in section 3.5.
- A horizontal line from the value of the microtube length on the vertical axis is drawn to intercept the line representing the required coil diameter. Interpolation may be used for intermediate values.
- From the point of interception, a line is drawn vertically to intersect the N_L - axis, which determines the number of coils. The actual number of coils taken is the nearest integer number (lower) to the point of interception on the horizontal axis.
- Project the number of coils on the vertical axis representing (γ) to obtain a new (θ) value as shown earlier.
- The procedure is repeated starting from the new (θ) until the number of coils is determined. If the number of coils equals the previously determined one, it is taken as the required number of coils, and the

last length of microtubes obtained is the required length.

- If the number of coils is different, the solution is repeated with the new value of (θ) until the number of coils is equal for two consecutive trials and this is taken as the required number of coils, and the last microtube length determined is the required length.
- The procedure is repeated for all microtubes throughout the network, which begins with the reference points (γ'), (f/d) and (v) in the Nomographs. The value of the total head in the lateral at the microtube inlet (H) is the only change in the design steps to determine different values of (θ). For each value of (θ) the values of the microtube lengths and the number of coils could be determined as explained earlier.

Figures (3.18a & 3.18b) show the design steps using the modified design Chart and Nomographs.

3.9 MICROTUBE LENGTHS USING COMPUTER PROGRAMMING

The purpose of this section is to demonstrate the use of computers in determining microtube lengths for those who have access to computing system. Computer program may be used to obtain rapid and precise results in calculating the lengths of the microtubes. The total head at microtube inlet (H_i) and the discharge passing through must be known for the calculation of the microtube length (i). The method of design depends on whether coils are used or not. In the absence of

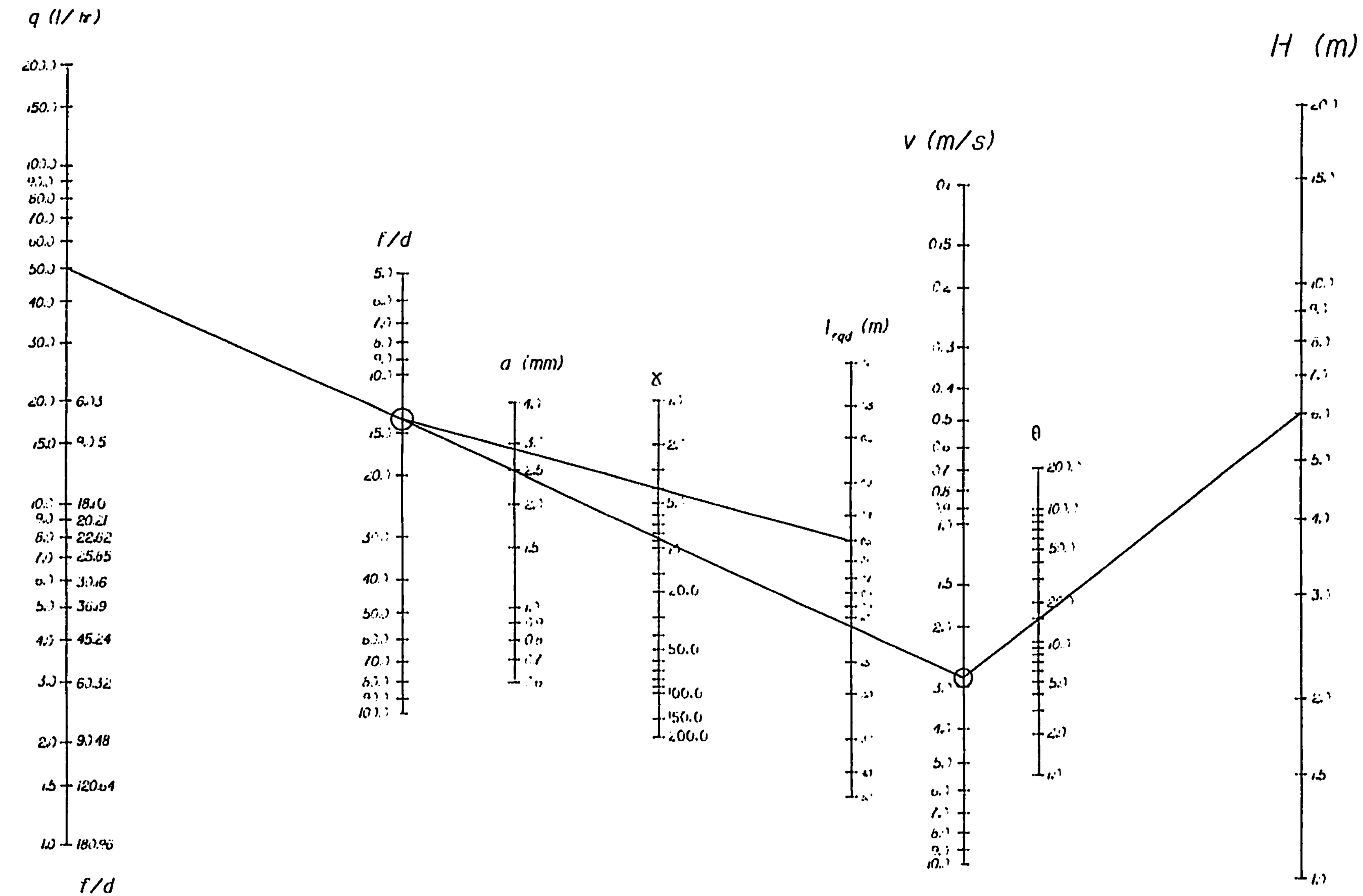


Figure (3.18.a) Modified Nomograph Design Steps

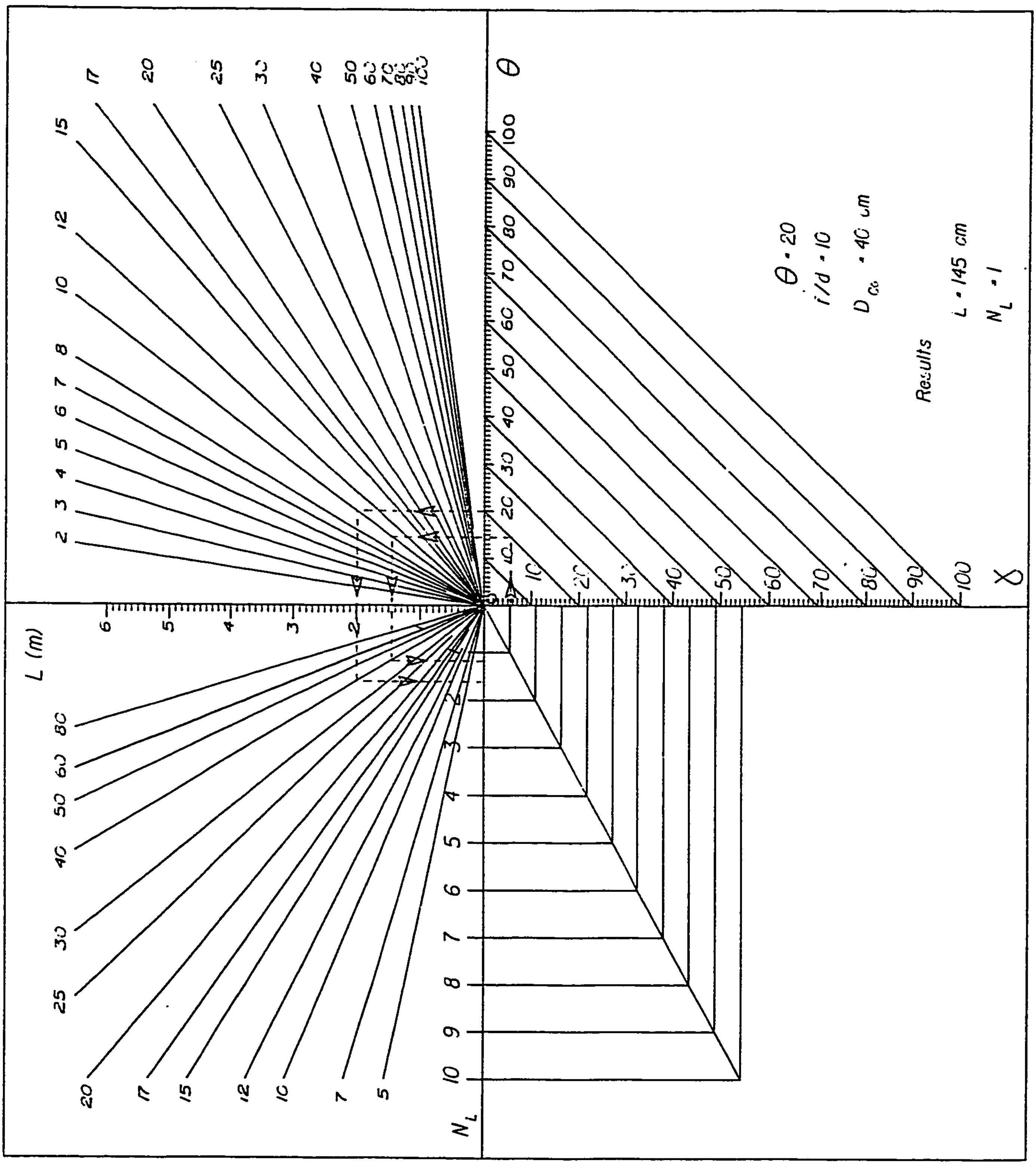


Figure (3.18.b) Modified Design Chart Steps

coils, the calculations are done directly while a trial and error method is used if coils are used. Both methods are described below.

3.9.1 Microtube design without coils

As it was presented earlier, the total head in lateral at the microtube inlet (H) is expressed by Equation (2.3), where minor losses are not separated from the total head.

$$H = \frac{f\ v^2}{2\ d\ g}\ L \qquad (2.3)$$

Denote $\frac{f\ v^2}{2\ d\ g}$ as (J) (the total head per unit length), which is the same for all microtubes in a given lateral. Equation (2.3) can be reformulated as

$$H = J * L \qquad (3.25)$$

Equation (3.25) is rearranged as:

$$L = \frac{H}{J} \qquad (3.26)$$

For the microtube (i), the length can be calculated from the following equation

$$L(i) = \frac{H(i)}{J} \qquad (3.27)$$

A subroutine has been developed to calculate the friction coefficient for microtubes in case of laminar and turbulent flows. Figures (A.1a & A.1b) in Appendix A show the flow chart and the computer program

used for calculating the friction coefficient in microtubes.

Another subroutine has been developed to calculate the microtube lengths without coils. Figures (A.2a & A.2b) in Appendix A show the subroutine and the computer program used for calculating the microtube lengths without coils.

3.9.2 Microtube design with coils

Microtube design using coils is a general case of the design without coils. The procedure starts by assuming absence of coils, thus the required microtube length (l_{rqd}) is calculated. Knowing the coil's diameter, which is determined or assigned by the designer, one can calculate the number of coils to be used after subtracting the required length from the calculated microtube length.

$$N_L = \frac{L(i) - l_{rqd}}{\pi\, D_{co}} \qquad (3.28)$$

The head loss due to coiling is

$$h'_{co} = k\, N_L\, \frac{v^2}{2\, g} \qquad (3.23)$$

where

h'_{co} = first trial head loss due to coiling

Since the number of coils has been calculated depending on the non-coiled length, it is necessary to subtract the coil loss from the

operating head and determine a new microtube length with (N_L) coils.

$$L'(i) = \frac{(H(i) - h_{co})}{J} \tag{3.29}$$

where

$L'(i)$ = new adjusted microtube length with coils

The procedure is repeated until two consecutive values of (N_L) are equal, which is the number of coils required and the last calculated microtube length. L(i) is the final length of the microtube length with coils. A subroutine has been developed to calculate both microtube lengths with and without coils. In the case of using coils, the coil diameter is set as the designer wishes, while for absence of coils the coil diameter is set to infinity ∞). For the program, the coil diameter could be set at value of 10 meters instead of (∞) to simplify the data entry, and the lengths of the microtubes will not exceed 10 meters from a practical point of view.

Figures (A.3a & A.3b) in Appendix A show the flow chart and subroutine used to calculate the microtube lengths with and without coils.

3.10 MICROTUBE EXPERIMENTAL VERIFICATION

Laboratory experiment was conducted to test the hydraulic relationships used in the development of the design Chart as well as the

computer program.

Two microtubes diameters (3.0 mm, 3.8 mm); Saudi market available; were used in the experiment. Five different operating heads; (115, 130, 145, 160, and 175 cm); were applied for three different microtube lengths (50, 100, 200 mm) for both diameters.

The microtube discharge was measured in each experimental run and compared with the calculated discharge under similar conditions.

3.10.1 Experimental Set-up

A tube of (18 cm) internal diameter and (2.25 m) long was used for the experiment. This tube was placed vertically and the bottom was sealed. The tube was provided with a control valve at the bottom. A manometer was attached on the surface of the tube to show the water level inside the tube.

The microtube was inserted about 25 cm from the bottom end into the outside surface of the vertical tube. The microtube was kept horizontally to prevent any head gain or loss due to change in elevation in the microtube.

A small submerged pump (8 l/min) was used to provide the tube with a continuous flow of water during the experiment. A graduated cylinder and a stop watch were used for the determination of the microtube discharge. Figure 3.19 shows a sketch of the microtube

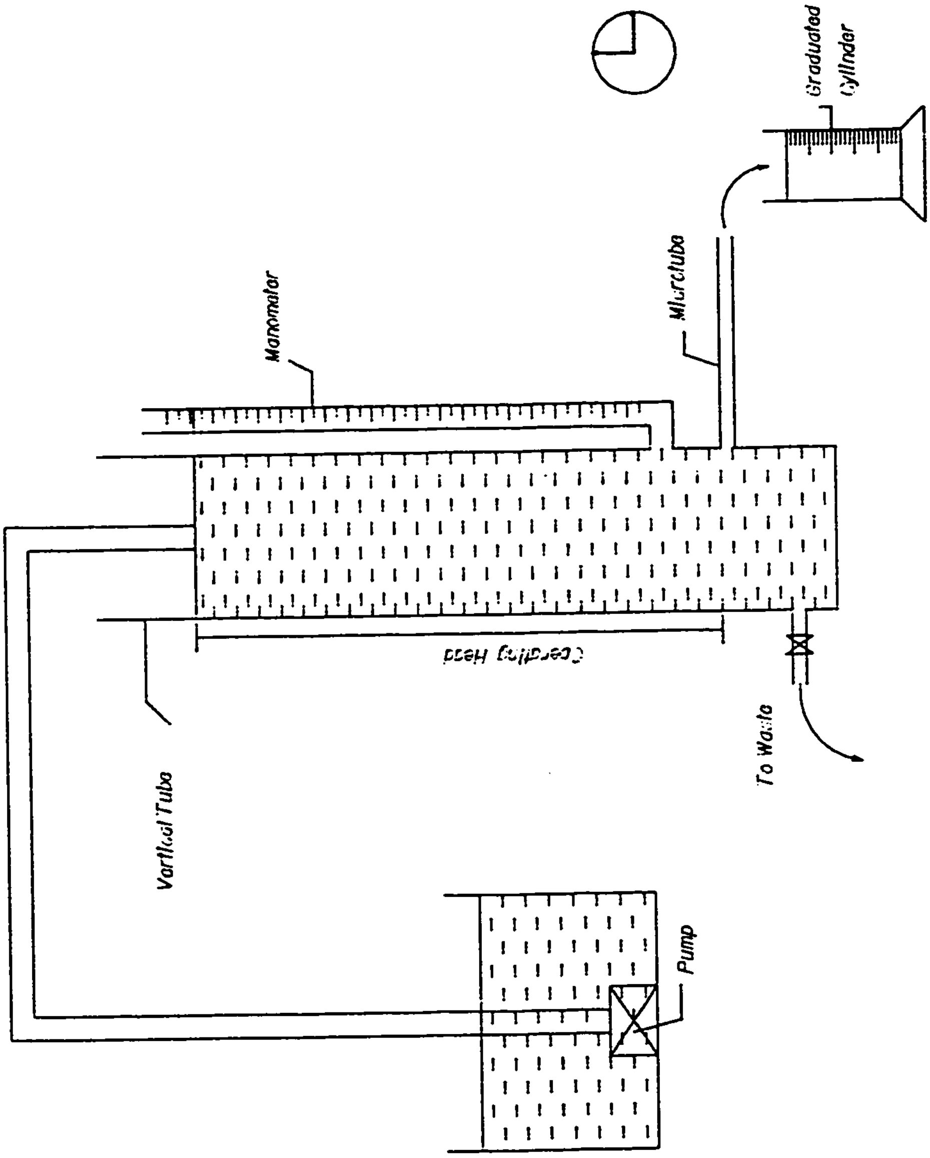


Figure (3.19) The Microtube Experimental Set-up

experimental set-up.

3.10.2 Procedure

Each of the microtubes were cut sharply at both ends. These microtubes were inserted for different runs into the surface of the vertical tube and sealed. The pump was then started and the required operating head was reached by adjusting the control valve. The microtube flow was continued until stabilization was reached, then the volume of the water in two minutes was measured using the (2000 ml) graduated cylinder.

The experiment was repeated for the other operating heads using the same microtube. The whole procedure was applied for the other microtubes. The experiment was conducted at 20-22°C water temperature. Tables (3.3 & 3.4) show the amount of water measured in two minutes for (3.0 mm) and (3.8 mm) microtube diameters; respectively.

3.10.3 Experimental Results

The volume of water (V) is expressed as a discharge in (m^3/s) by dividing the volume over (2*60*1000). Tables (3.5 & 3.6) show the experimental values of the microtube discharge for each run.

The total head was expressed earlier by Equation (2.3) as follows:

Operating head (cm)	Microtube length (cm)		
	50	100	200
115	1.660	1.170	0.820
130	1.770	1.260	0.870
145	1.890	1.330	0.930
160	1.995	1.421	0.985
175	2.098	1.490	1.030

Table (3.3) The amount of water in liters measured in 2 minutes for 3.0 mm microtube diameter

Operating head (cm)	Microtube length (cm)		
	50	100	200
115	3.160	2.265	1.610
130	3.340	2.400	1.725
145	3.570	2.565	1.825
160	3.790	2.730	1.935
175	3.960	2.885	2.025

Table (3.4) The amount of water in liters measured in 2 minutes for 3.8 mm microtube diameter

Operating head (cm)	Microtube length (cm)		
	50	100	200
115	49.80	35.10	24.60
130	53.10	37.80	26.10
145	56.06	39.90	42.60
160	59.30	42.60	29.55
175	62.94	44.70	30.90

Table (3.5) The experimental discharge for (3.0 mm) microtube diameter

Operating head (cm)	Microtube length (cm)		
	50	100	200
115	94.80	67.95	48.30
130	100.20	72.00	51.75
145	107.10	76.95	54.75
160	113.70	81.90	58.05
175	118.80	86.55	60.75

Table (3.6) The experimental discharge for (3.8 mm) microtube diameter

$$H = f\, v^2 \frac{L}{d^2 g} \qquad (2.3)$$

The flow type was assumed to be turbulent in all the experimental runs and then checked after calculating the velocity of flow, where Reynolds' numbers were determined. The friction coefficient in turbulent flow was expressed by Blasuis Equation (2.4) as follows:

$$f = \frac{0.316}{R^{0.25}} \qquad (2.4)$$

The Reynolds' number is expressed by the following equation:

$$R = v \frac{d}{\nu} \qquad (3.36)$$

Substitute Equations (2.4) and (3.36) in Equation (2.3) and using metric units for the specific gravity; Equation (2.3) becomes:

$$H = \frac{0.316\, \nu^{0.25}\, v^2 L}{v^{0.25} d^{0.25} 2\, g}$$

$$H = \frac{5.04317*10^{-4}\, v^{1.75} L}{d^{1.25}}$$

$$v^{1.75} = \frac{1963.4\ H\ d^{1.25}}{L}$$

$$v = \left(\frac{1963.4\ H\ d^{1.25}}{L}\right)^{0.571}$$

$$v = \frac{75.912\ H^{0.571} d^{0.714}}{L^{0.571}} \qquad (3.37)$$

The microtube discharge is expressed in the form of the flow velocity as follows:

$$q = \frac{\pi d^2}{4} v \qquad (3.38)$$

substitute the value of the flow velocity from Equation (3.37) in Equation (3.38)

$$q = \frac{\pi d^2 \; 75.912 \; H^{0.571} d^{0.714}}{4 \; L^{0.571}}$$

$$q = \frac{59.62 \; d^{2.714} \; H^{0.571}}{L^{0.571}} \quad (m^3/s) \qquad (3.39)$$

$$q = \frac{59.62 \; d^{2.714} \; H^{0.571}}{L^{0.571}} \; 1000*3600 \quad (l/h)$$

$$q = \frac{214633929 \; d^{2.714} \; H^{0.571}}{L^{0.571}} \qquad (3.40)$$

Tables (3.7 & 3.8) show the calculated values of the microtube discharge for each experimental run. The experimental and calculated discharges were plotted on the same axis for both microtube diameters. These values are shown in Figures (3.20 & 3.21).

3.11 SENSITIVITY ANALYSIS

The purpose of the study of the sensitivity analysis is to know the effect of change in one parameter on the other parameters. The study is therefore, valuable for finding suitable solutions for any variables by

Operating head (cm)	Microtube length (cm)		
	50	100	200
115	49.10	33.06	22.25
130	52.67	35.51	13.87
145	56.06	37.74	25.40
160	59.30	39.92	26.87
175	62.41	42.01	28.28

Table (3.7) The calculated discharge for (3.0 mm) microtube diameter

Operating head (cm)	Microtube length (cm)		
	50	100	200
115	93.41	62.88	42.33
130	100.18	67.44	45.40
145	106.63	71.78	48.32
160	112.79	75.93	51.11
175	118.70	79.91	53.79

Table (3.8) The calculated discharge for (3.8 mm) microtube diameter

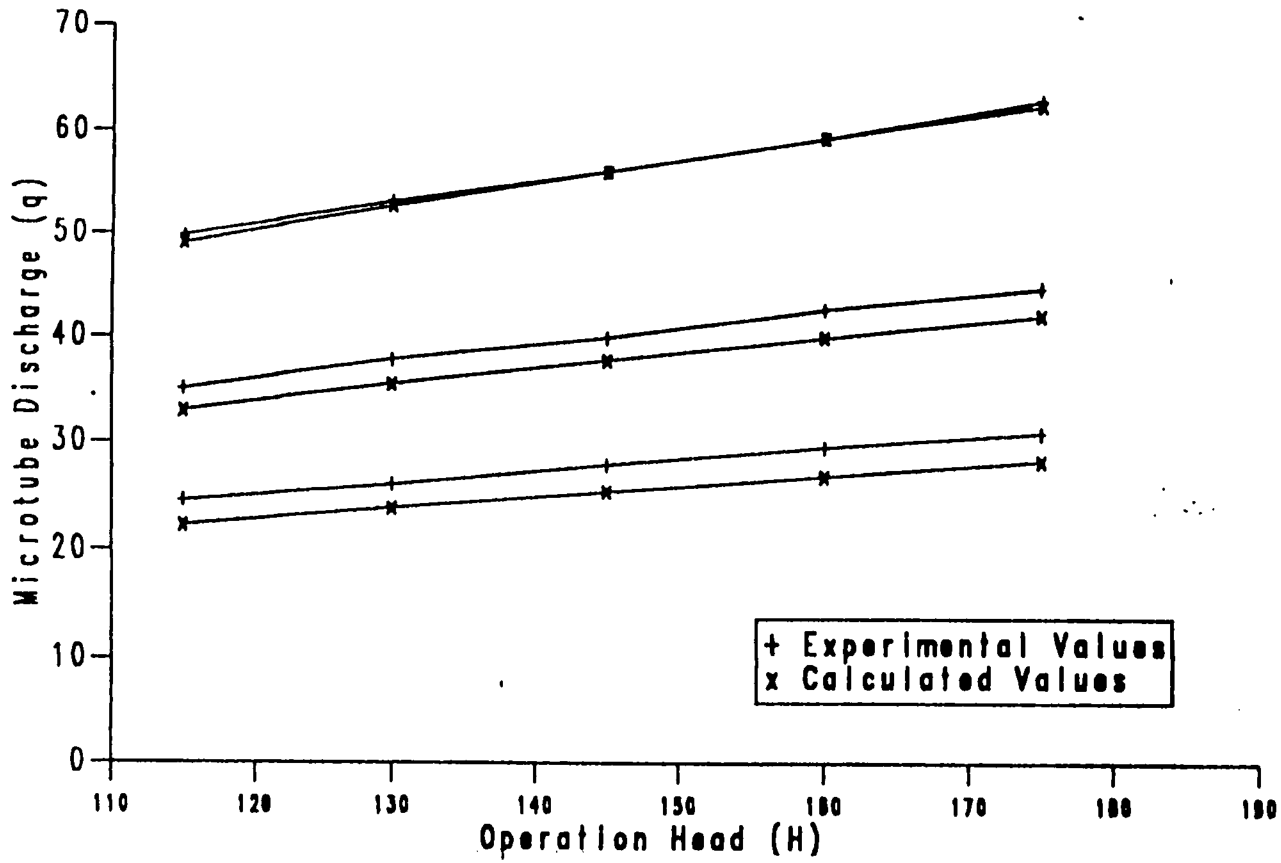


Figure (3.20) Experimental and Calculated Discharges

for (3.0 mm) Microtube Diameter.

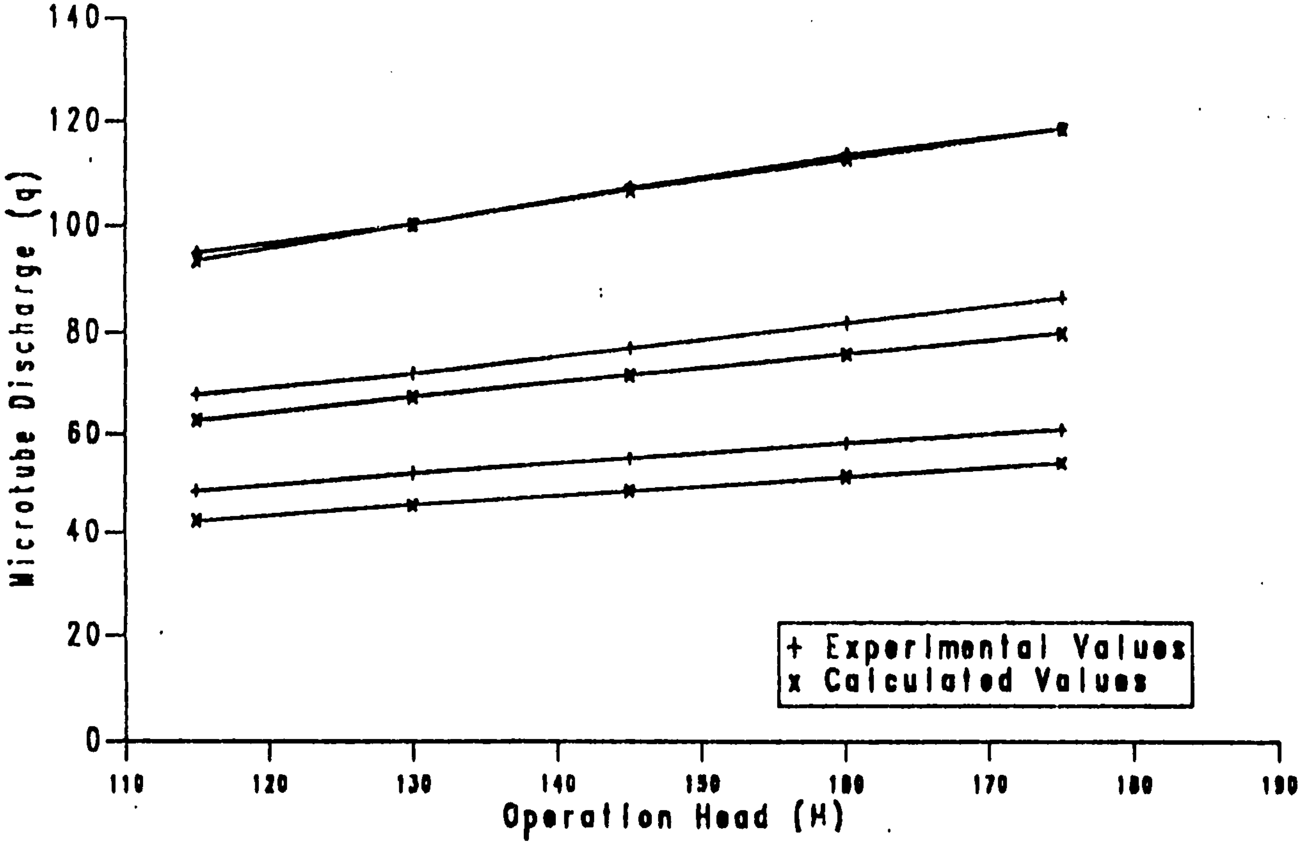


Figure (3.21) Experimental and Calculated Discharges

for (3.8 mm) Microtube Diameter.

changing the various parameters. In the case of turbulent flow in microtubes, Equation (3.39) has been formulated to relate various parameters, such as microtube length, diameter, discharge, and operating head at the microtube inlet.

$$q = \frac{59.62\ d^{2.714}\ H^{0.571}}{L^{0.571}} \qquad (m^3/s) \qquad (3.39)$$

As shown from the Equation (3.39), the discharge (q) is directly proportional to the operating head at the microtube inlet (H) to the power 0.571, therefore if (H) is doubled, (q) will almost be half the original value.

The discharge (q) is inversely proportional to the length (L) to the power 0.571, therefore if the microtube length is doubled (q) will be almost two third the original value. The microtube diameter (d) has a great influence on the discharge as (q) is proportional to microtube diameter (d) to the power 2.714 which means an increase of about six times in the amount of the discharge as the microtube diameter is doubled.

The operating head at the inlet (H) is proportional to the length (L) and an variation in (H) causes a similar variation in the length (L).

In the case of laminar flow; if Equation (2.6) for laminar flow

friction coefficient is substituted instead of Blasuis equation in Equation (2.3) and substitute Equation (2.3) in Equation (3.38), we will get the following equation:

$$q = \text{constant} \frac{H\ d^2}{L} \qquad (3.40)$$

As shown from Equation (3.40), the discharge (q) is directly proportional to the operating head (H) and inversely proportional to the microtube length (L). It is also shown that any variation in the head or in the length causes the same variation in the discharge because the relationship is linear between the discharge and the head and between the discharge and the length.

The effect of the microtube diameter on the microtube discharge is very large. It is seen from the equation that a variation of the diameter causes 16 times variation in the microtube discharge.

In summary, the following have been noticed from the study of the system sensitivity:

- microtube discharge is much more sensitive to all parameters in laminar flow than in turbulent flow;
- the effect of the operating head and the length on the discharge are the same and - the effect of the microtube diameter is very high compared to other parameters.

CHAPTER (4)

DESIGN OF LATERAL WITH MULTI MICROTUBE USING COMPUTER PROGRAMMING

4.1 INTRODUCTION

Laterals convey water from submains to the distributors. They are generally pipes of (low density Polyethylene (PE) or small diameter Poly vinyl chlorides (PVC)). Distributors are usually fixed on the laterals at equal spacings. From the practical experience the outlet spacings are all equal except for the first spacing length which is normally half of the other regular spacing length (1,2).

The sizing of tubes for a trickle irrigation lateral is determined by a process based on numerous factors. These factors are crop water requirements, climate, soil properties, hydraulic principles, emiter flow characteristics, field size and elevation, total head at the lateral inlet and irrigation and tubing economics and some criteria of water application uniformity which is related to several aforementioned factors (2).

4.2 LATERAL DESIGN CRITERIA

Many parameters govern the design of lateral. Some of these parameters are fixed for a certain network; for example; land slope, number of outlets and the spacings between outlets. Other parameters

can be estimated like the lateral diameter, the microtubes' discharges and the total head at the lateral inlet. The estimated parameters are completely related to each other and need different computational procedures.

Always two of the three design parameters are known and the third parameter is required to be calculated. The multiple combination of the lateral design cases are shown in Figure 4.1.

The three possible cases of lateral design could be easily identified and solved by using computers. A computer program in FORTRAN IV language has been developed to compute the needed unknowns for the design of the lateral. The program has been developed to calculate the total head distribution along the lateral, and has been linked with the previously developed subroutines for microtube lengths determination. Thus, the developed computer output gives the unknown parameters; the diameter, the total head at the lateral inlet, microtube discharge, the total head distribution and the microtube lengths for each of the three cases.

4.2.1 Case I Known microtube discharge (q) and operating head at the microtube inlet (H) and unknown microtube diameter (d)

This is the common design case where the discharge is known from the plant water requirements. The total head at the lateral inlet may be assumed at the begining of the design or governed by the submain total

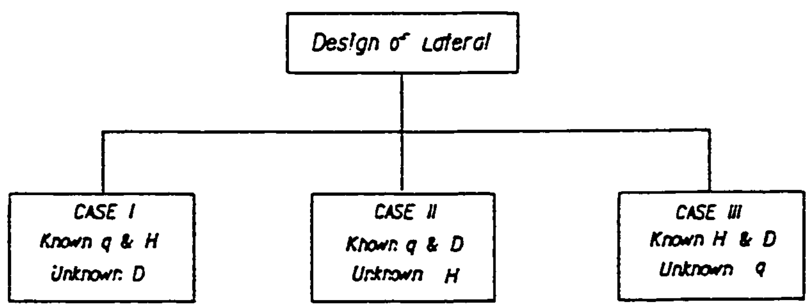


Figure (4J) The Three Lateral Design Cases

head. The designer is left with the determination of the lateral diameter.

The procedure begins with the assumption of a lateral diameter from the commercially available sizes. The second step is to determine the total head distribution along the lateral.

Once the total head along the lateral is known, the microtube lengths can be determined by the procedure detailed in Chapter (3).

If the minimum calculated microtube length is less than the required microtube length, the suggested solutions are:

- increase the microtube diameter or
- decrease the required microtube length (l_{rqd}) (if possible).

Sometimes the designer prefers to keep the pressure head variation along the lateral within a certain range of variation although he is using microtubes. In this case he can check the pressure head variation directly from the computer output and select the suitable lateral diameter for the required variation. Figure 4.2 shows the macro chart of case I design steps.

4.2.2 Case II Known microtube discharge (q) and microtube diameter (d), and unknown operating head at the microtube inlet (H)

Usually the plant water requirements are known in most cases of the design of the lateral. Some designers prefer to assume a diameter for

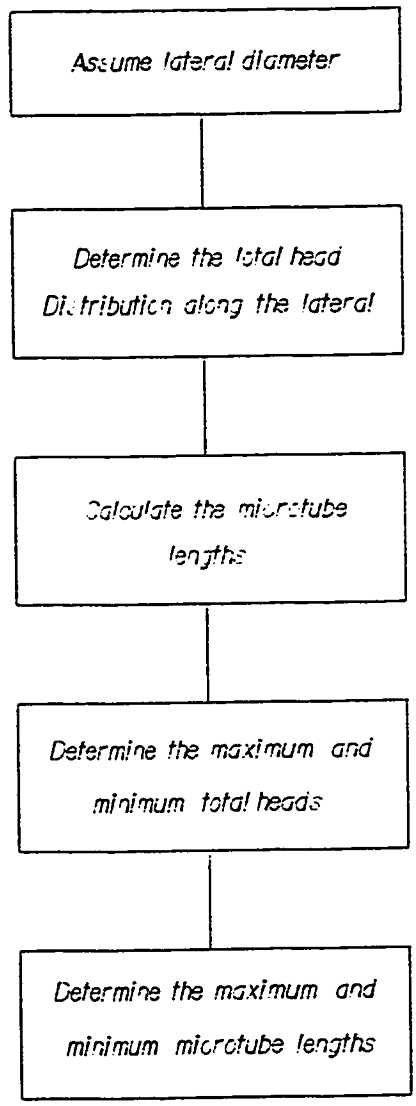


Figure (4.2) Macro Chart for Case I

the first lateral in the network by experience or calculate it as described in case I. This assumed lateral's diameter is applied to the whole network to simplify calculations and installation. In such a design, the lateral's diameter and the microtube discharges are known and the only parameter to be calculated would be the minimum total head at the lateral inlet.

The solution differs for two cases. The first case occurs when the lateral is horizontal or has an upward slope. The second case occurs when the lateral has a downward slope.

In the case of horizontal or an upward lateral slope, the highest value of total head will be at the lateral entrance and the lowest at the lateral end, as shown in Figures (4.3 & 4.4).

In case of a downward slope of the land, the lowest value of the total head will be either at the lateral end, the lateral inlet, or any where in between depending on the lateral's length, its slope, and the microtube discharges. Therefore, the method of the solution will differ with the variation in the position of the lowest total head point. This cannot be easily determined for the above case (3). Different positions of the lowest total head in the case of downward slopes are shown in Figures (4.5, 4.6 & 4.7).

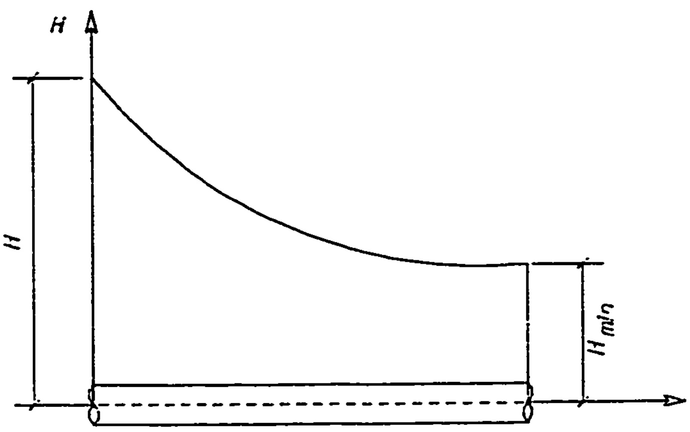


Figure .4.3' Minimum Total Head at the Lateral End in the Case of Horizontal Slope

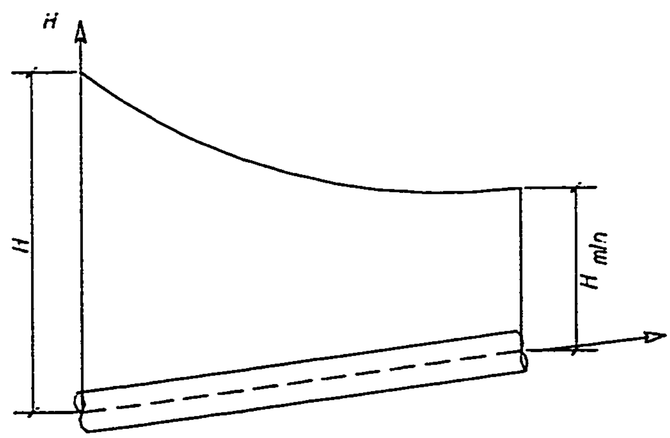


Figure (4.4) Minimum Total Head at the Lateral End in the case of Upward Slope

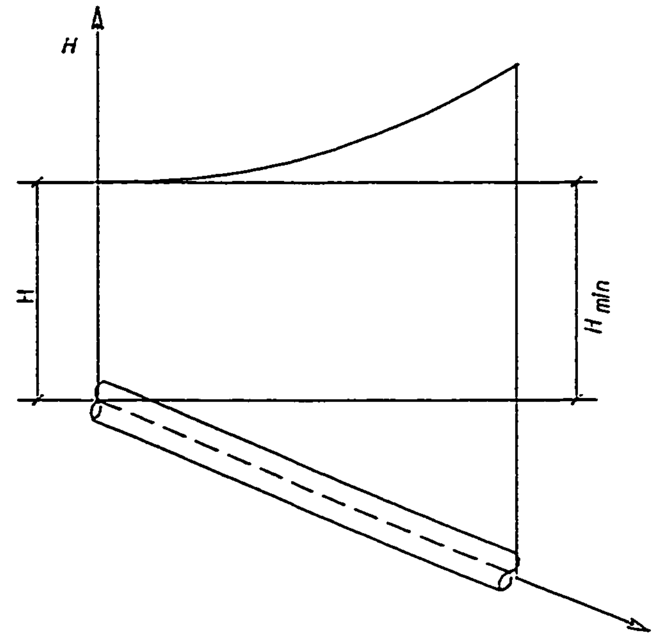


Figure (4.5) Minimum Total Head at the Lateral Entrance in the Case of Downward Slope

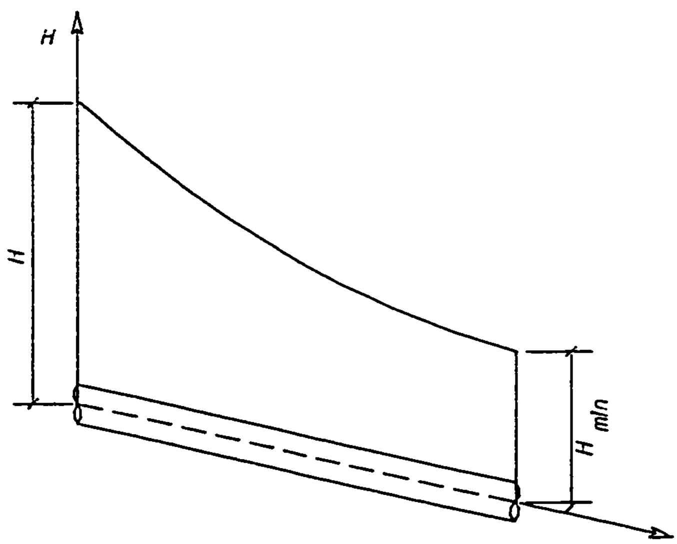


Figure (4.6) Minimum Total Head at the Lateral End in the Case of Downward Slope

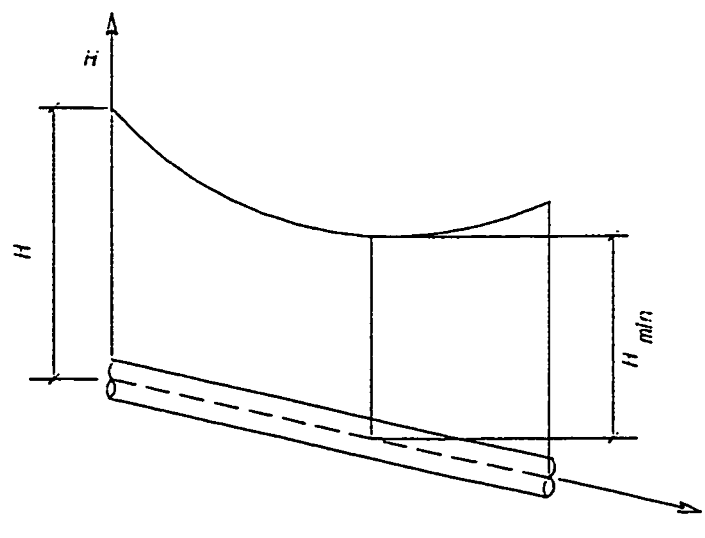


Figure (4.7) minimum Total Head Between the Lateral's Ends in the Case of Downward Slope

1 - Lowest total head at the entrance or end of the lateral:

Since the position of the lowest total head is known, (lateral inlet or end) the computations for obtaining (H) are started from these of known position. The solution is obtained by determining the required minimum value of the total head; defined as (H_{min1}). This concept and the determination of the required minimum total head (H_{min1}) will be discussed later. The calculation of the total head at the next point is done by considering the head loss due to friction and the difference due to changes in elevation. The calculations of the total head at each point move from point to point until the total heads are calculated along the whole lateral.

2 - Lowest total head between inlet and end of the lateral:

The total head distribution along the lateral in this case cannot be determined directly because the location of the minimum value of the total head (H_{min1}) where the calculations begin; is unknown. This location can be determined by starting the computation from all possible locations as the minimum total head (H_{min1}) and check which one of these locations gives the minimum value of the total head at its location.

A procedure can be followed where a higher total head is assumed at the lateral entrance and where the change in the head due to elevations and frictions are added as one proceeds towards the end.

Thus, the total head distribution along the lateral is calculated. From the curve the lowest total head (H_{min}) is determined. The next step is to calculate the difference between the lowest total head (H_{min}) and the required lowest total head (H_{min1}). The difference becomes the shift between the assumed curve from the required curve. Thus, the last step is to subtract the difference between (H_{min}) and (H_{min1}) from the assumed total head at all points along the lateral to determine the required total head distribution. Figure 4.8 shows the assumed and required total head distributions.

For the simplification of calculations and to have only one procedure for case II, the same steps will be followed in all lateral slopes. The last step after the total head distribution calculations is to measure the lengths of the microtubes as mentioned in chapter (3). Figure 4.9 shows the macro flow chart for case II design steps.

4.2.3. Case III Known operating head at the microtube inlet (H) and microtube diameter (d) and unknown microtube discharge (q)

In this case the lateral diameter and the total head at the lateral entrance are known. This is true when the known total head at the lateral inlet is equal to the total head at the submain. The designer assumes a lateral diameter to be used and this diameter must be the same for the whole network. Thus, the only unknown parameter is the

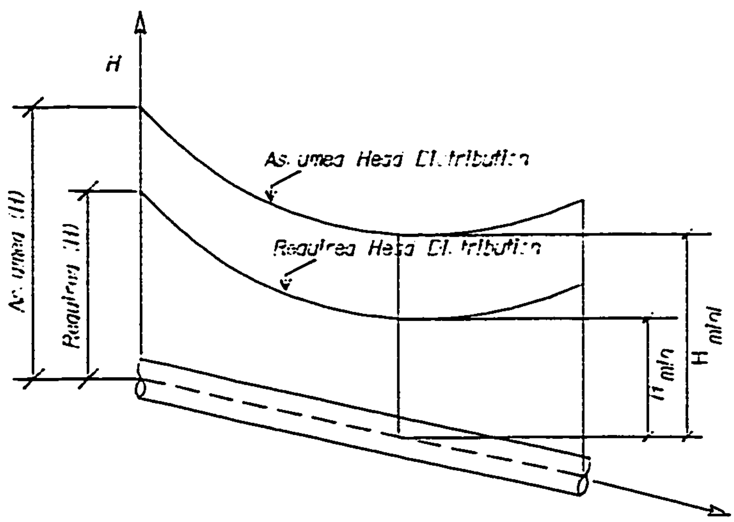


Figure 4.6: Assumed and Required Total Head Distribution Along the Lateral

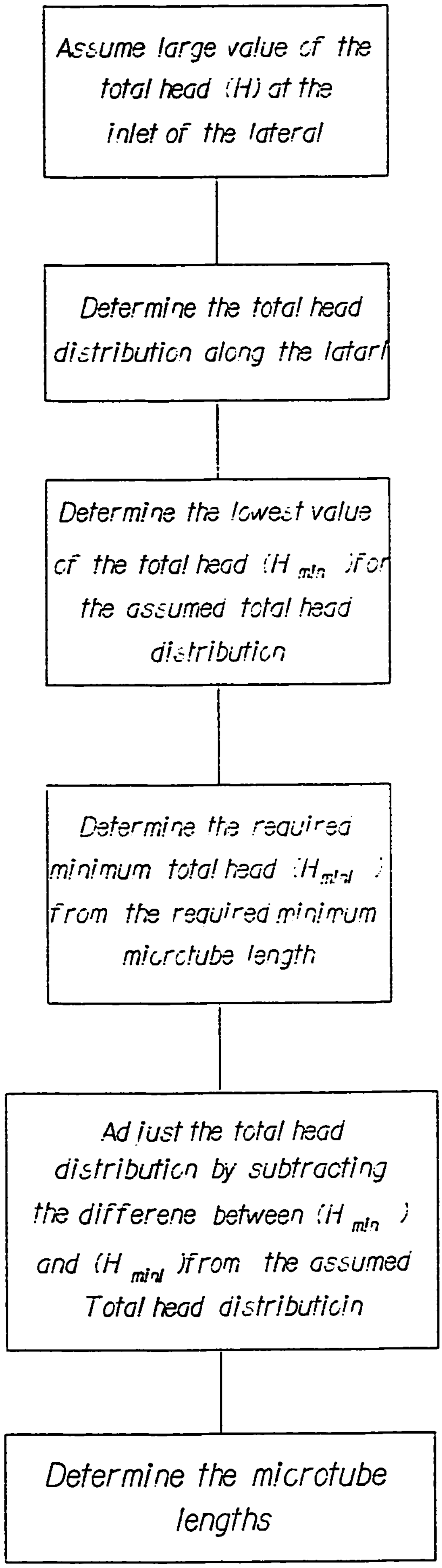


Figure (4.9) Macro Chart for Case II

maximum microtube discharges.

A trial and error method can be used in this case because of the large number of equations involved, and these equations are not easily formulated due to their complexity. Additional complications involved are the unknown flow type, the position, and the value of the lowest total head. Therefore, the first solution step is to assume a value for the discharge and the problem is solved as a modified case II with two unknowns, which are the lateral's diameter and the assumed microtubes discharges.

Prior to the calculation of the microtube lengths, the designer must be sure of the calculated total head value at the lateral inlet (HH). If the value of (HH) equals the given value of the total head (H) in the problem, the assumed discharge, therefore, will be the actual discharge. But if they are different, a new assumed value for the discharge is assumed to get a closer value for the known total head at the lateral inlet. For a better assumption for the discharge in order to get rapid computation conversion a relationship between the lateral discharge (Q) and the total head at the lateral inlet (H) will be developed.

Watters and Keller (26) have shown that for small diameter smooth pipes used in trickle laterals, Darcy-Weisbach equation combined with; Blasius equation (in case of turbulent flow) or laminar flow equations (in case of laminar flow); gives accurate predictions of head loss due to

friction. Darcy-Weisbach equation is expressed as follows:

$$H_{f_i} = \frac{8 f Q_i^2 X_i}{\pi^2 D^5 g} \qquad (4.1)$$

where

H_{f_i} = head loss due to friction in the pipe segment(i)

X_i = length of the lateral segment(i)

Q_i = lateral discharge at the pipe (i) cross section

= (n-i+1) * q

q = microtube discharge

n = number of microtube along the lateral

D = lateral diameter

The friction coefficient (f) is calculated using Blasius equation as follows:

$$f = \frac{0.32}{R^{0.25}} \quad \text{(Blasius Equation)} \qquad (2.3)$$

Assuming a turbulent flow in most of the cases, the friction coefficient for laterals is the same as in microtubes and can be calculated using Equation (3.9)

$$f = \frac{0.41\ D^{0.25}}{Q^{0.25}} \qquad (3.9)$$

Substituting the value of (f) from Equation (3.9) in Equation (4.1)

$$H_{f_i} = \frac{0.41\ D^{0.25}}{Q_i^{0.25}} * \frac{8\ Q_i^2\ X_i}{\pi^2\ D^5\ g}$$

$$H_{f_i} = \frac{0.224\ Q_i^{1.75}\ X_i}{D^{4.75}\ g} \tag{4.2}$$

The total head at the lateral inlet can be calculated by adding the friction loss for all pipe segments, the total head at the lateral end and the head loss or gain due to change in elevation. This relation is expressed by the following equation

$$H = H_{end} + Z + \sum_{i=1}^{n} H_{f_i} \tag{4.3}$$

Where

H_{end} = total head at the lateral end

Z = difference in elevation between the lateral inlet and end

$\sum_{i=1}^{n} H_{f_i}$ = total friction head loss for all pipe segments

Assuming all the pipe segments have the same length (x) and substituting the value of the friction head loss (H_{f_i}) from Equation (4.2) in Equation (4.3) we get the following equation:

$$H = H_{end} + Z + \frac{0.244\ X}{D^{4.75}\ g} (\ Q_1^{1.75} + Q_2^{1.75} + \ldots Q_n^{1.75}\ )$$

$$H = H_{end} + Z + \frac{0.244\ X}{D^{4.75}\ g} (\ (nq)^{1.75} + ((n-1)q)^{1.75} + \ldots q^{1.75}\ )$$

$$= H_{end} + Z + \left(\frac{0.244 \text{ X}}{D^{4.75} \text{ g}} \sum_{i=1}^{n} i^{1.75} \; q^{1.75} \right.$$

$$H = c_1 + c_2 \, q^{1.75}$$

Where

$$c_1 = \text{constant} = H_{end} + Z$$

$$c_2 = \text{constant} = \frac{0.244 \text{ X}}{D^{4.75} \text{ g}} \sum_{i=1}^{n} i^{1.75}$$

$$H \propto q^{1.75}$$

so

$$q \propto H^{0.571}$$

For a rapid conversion of the microtube discharge, a new discharge value is assumed as follows

$$q_n = q_o * \left(\frac{H}{HH} \right)^{0.571} \qquad (4.4)$$

Where

q_n = new discharge

q_o = old discharge

H = required total head

HH = calculated total head

Thus, new assumed values for the discharge are used to make the calculated total head at the lateral inlet (HH) almost equal to the given total head at the lateral inlet (H).

After the determination of the total head distribution along the lateral, the length of the needed microtube could be calculated as it was explained earlier. Figure 4.10 shows the macro chart for case III design steps.

4.3 BASIC SUBROUTINES NEEDED FOR THE PROGRAMMED LATERAL DESIGN

A lateral design program has been structured as a set of subroutines, which allows the use of each subroutine more than once and makes it much easier to build, follow and search for the errors. FORTRAN IV was used as the programming language in the developed program. The subroutines used in the program are presented in the following sections.

4.3.1 Subroutine for lateral friction coefficient (FRIC)

Proper evaluation of the frictional head loss in a lateral is essential to achieve optimum uniformity of emiter discharge. Flows in trickle irrigation laterals are always restricted to low Reynolds' numbers. Most designers are trying to avoid the transition zone in their design (6).

As it was presented earlier, Watters and Keller have shown that small diameter smooth pipes used in trickle laterals Darcy-Weisbach equation, gives accurate predictions of the friction head loss. The friction coefficient is determined by Blasius Equation (2.3) in the case of turbulent flow or by Equation (2.5) for laminar flow. The developed

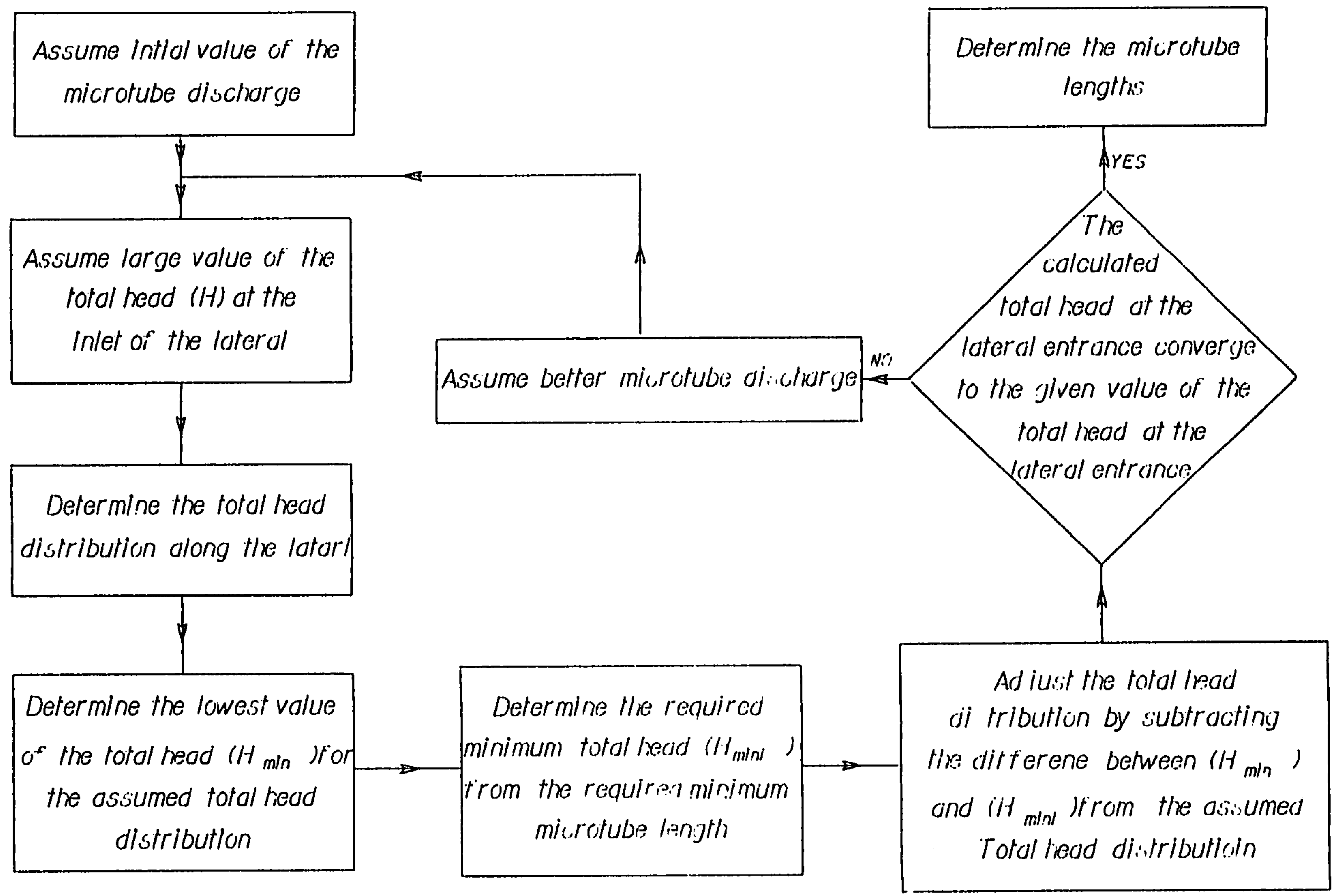


Figure (4.10) Macro Chart for Case III

flow chart and the subroutine for the lateral friction coefficient determination are identically the same as those of microtube friction coefficient given in Figures (A.1a & A.1b) in Appendix A.

4.3.2 Subroutine for total head distribution along the lateral (HEDIS)

A step by step procedure is used to determine the total head distribution along the lateral. The lateral used should have a known lateral diameter, known total head at its inlet and equal microtube discharges.

The total head at the node (i) can be calculated by subtracting the head loss due to friction (H_f) and the head gain or loss due to change in elevation (Z_i) from the total head of the upstream node ($H_{(i-1)}$). This relation is expressed by the following equation:

$$H_i = H_{(i-1)} - h_{f_i} - Z_i \qquad (4.5)$$

where

H_i = total head at the node (i)

$H_{(i-1)}$ = total head at the upstream node (i − 1)

H_{f_i} = head loss due to friction

Z_i = change in elevation between node (i) and node (i − 1) (+ve upward & -ve downward)

$= S_i * X_i$

S_i = land slope at the pipe segment(i)

The flow chart and the subroutine for the total head calculations are given in Figures (A.4a & A.4b) in Appendix A.

4.3.3 Subroutine for minimum total head from the required microtube length (MINI)

As it has been described previously, the required minimum microtube length (l_{rqd}) is the minimum microtube length needed to convey water from the lateral to the plant.

The required total head corresponding to the required microtube length can also be expressed by Darcy-Weisbach equation as follows:

$$H_{min1} = f \frac{v^2 \, l_{rqd}}{2 \, d \, g} \qquad (2.6)$$

Where

H_{min1} = minimum head loss due to friction

The flow chart and the subroutine for determining the minimum required total head are given in Figures (A.5a & A.5b) in Appendix A.

4.3.4 Subroutine for minimum value of a set of values (XXMIN)

A subroutine has been developed to determine the minimum value of a set of values. This subroutine helps in the determination of the minimum microtube length and the minimum total head along the lateral.

The flow chart and the subroutine for determining the minimum value of a set of values are given in Figures (A.6a & A.6b) in Appendix A.

4.3.5 Subroutine for maximum value of a set of values (XXMAX)

Another subroutine has been developed to pick the maximum value from a set of values which helps in finding the maximum microtube length and the maximum total head along the lateral.

The flow chart and the subroutine for determining the maximum value of a set of values are given in Figures (A.7a & A.7b) in Appendix A.

4.3.6 Subroutine for adjusting the total head distribution (ADJ)

A subroutine has been developed to adjust the total head distribution along the lateral. The difference between the assumed minimum total head (H_{min}) and the required minimum total head (H_{min1}) is subtracted from all total heads along the lateral. Figures (A.8a & A.8b) in Appendix A show the flow chart and the subroutine for adjusting the total head distribution along the lateral.

4.4 APPLICATIONS ON LATERALS USING THE DEVELOPED COMPUTER PROGRAM.

The developed program has the capability to design more than one lateral at a time. The land slope can be introduced in the program to specify the the design cases and land slope.

In addition to the previously mentioned subroutines, other subroutines have been linked to the program to write the output in an appropriate format. Figure A.9 in Appendix A shows the developed computer program for the lateral design.

4.4.1 Application on case 1

If it is required to determine the suitable lateral diameter for a (7 m) operating head at the microtube inlet and (20 l/h) microtube discharge. The selected microtube diameter is (1.5 mm) and the coil diameter is (10 cm). The number of microtubes along the lateral are 10 with (10 m) spacing and (5 m) for the first. The required minimum microtube length is (50 cm). The land shape is flat.

Assume the designer chooses lateral diameter equals to (14 mm). Figure A.10 in Appendix A showes the results, where the solution is infeasible. The computer output suggests to either; increase the lateral diameter, increase the microtube diameter or decrease the required minimum microtube length.

Figure A.11 in Appendix A shows the three suggested solutions by the computer output, where, in the first solution the lateral diameter was increased from (14 mm) to (20 mm). In the second solution the microtube diameter was increased from (1.5 mm) to (2.0 mm). In the third solution the required minimum microtube length was decreased from (50 cm) to (40 cm).

4.4.1 Application on case 2

If it is required to determine the operating head at the microtube inlet (H) for (40 l/h) microtube discharge and (14 mm) lateral diameter. The coil diameter is (10 cm) and the required minimum microtube length is (50 cm). The number of microtubes along the lateral are 10 with a (10 m) spacing and (5 m) for the first lateral segment. The microtube diameter is (2.0 mm). The lateral has a uniform (0.005) upward slope.

Figure A.12 in Appendix A shows the results, where the required total head at the microtube inlet equals to (8.1879 m)

4.4.1 Application on case 3

If it required to determine the maximum discharge (q) for a (5 m) operating head at the microtube inlet (H) and (14 mm) lateral diameter. The required minimum microtube length is (50 cm). The number of outlets along the lateral is (10) with a (10) spacing and (5 m) spacing for the first lateral segment. The microtube diameter is (2.0 mm).

The land slope is (0.005) downward from the first lateral up to the fourth segment and horizontal from the fourth up to the eighth segment and (0.001) form the eighth segment up the end of the lateral. Figure A.13 in Appendix A shows the results, where the microtube discharge equals to (16.1354 l/h)

4.5 LATERAL EXPERIMENTAL VERIFICATION

Laboratory experiment has been conducted to verify the correctness of developed computer program for a lateral design with microtube emiters. It was proposed to simulate the field conditions by inserting microtubes in a lateral. The microtube discharges were measured for different applying heads at the lateral inlet.

4.5.1 Experimental Set-up

A lateral was placed horizontally and three microtubes have been inserted at (5,15 and 25 m) from the lateral inlet. Three different operating heads (175, 150 and 125 cm) have been applied at the lateral inlet. Two microtube diameters (3 mm and 3.8 mm) were used of different lengths to obtain a microtube discharge equals to (50 l/h) for (3.0 mm) microtube diameter and (80 l/h) for (3.8 mm) microtube diameter. Figure 4.11 shows the lateral experimental set-up.

4.5.2 Procedure

The microtube lengths have been computed by the developed

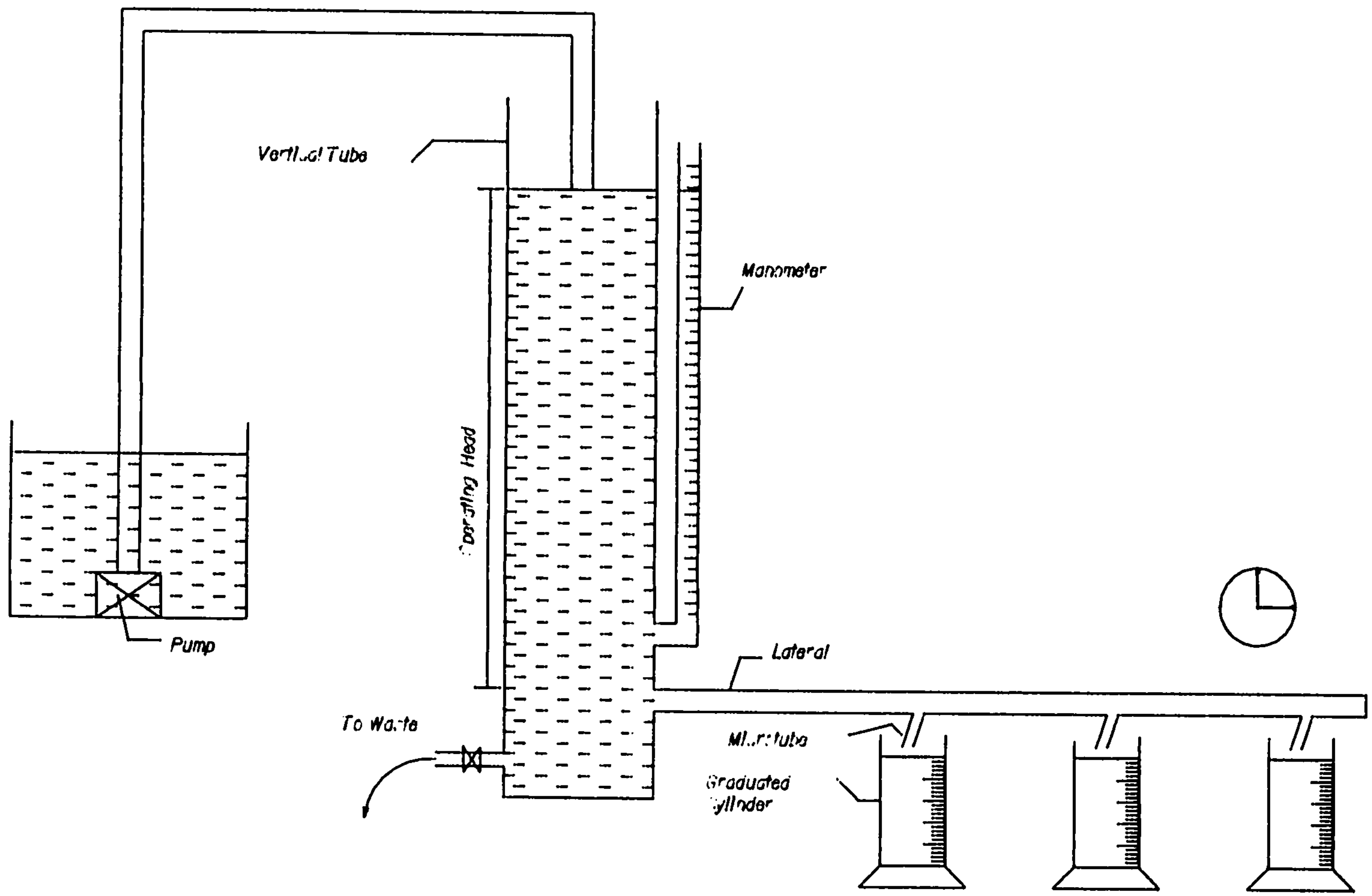


Figure (4.II) The Lateral Expelmental Set-up

program to obtain the required discharges. The volume of water in two minutes were measured by the use of graduated cylinder and stop watch. The microtube discharges were computed by dividing the amount of water over the duration of flow. Tables 4.1 and 4.2 show the volumes of microtube discharges for (3.0 mm) and (3.8 mm) respectively.

4.5.3 Experimental Results

The values of the computed microtube discharges were plotted versus the operating heads at the lateral inlet for the three microtubes along the lateral. Figures (4.12 & 4.13) show the bar charts for (3 mm and 3.8 mm) microtube diameters at different applied operating heat the lateral inlet.

It was obviously shown from Figures (4.12 & 4.13) that the experimental microtube discharges are almost the same as the desired values.

Operating head (m)	discharge (l/h)
1.22	79.58
1.25	80.02
1.28	80.58
1.47	81.34
1.50	80.63
1.53	80.37
1.72	80.98
1.75	81.55
1.78	82.67

Table (4.1) The Experimental Values of the Operating Head and the Microtube Discharges for (3.0 mm) Microtube Diameter

Operating head (m)	discharge (l/h)
1.22	50.63
1.25	50.03
1.28	49.86
1.47	51.34
1.50	50.63
1.53	50.02
1.72	51.78
1.75	50.85
1.78	50.60

Table (4.2) The Experimental Values of the Operating Head and the Microtube Discharges for (3.8 mm) Microtube Diameter

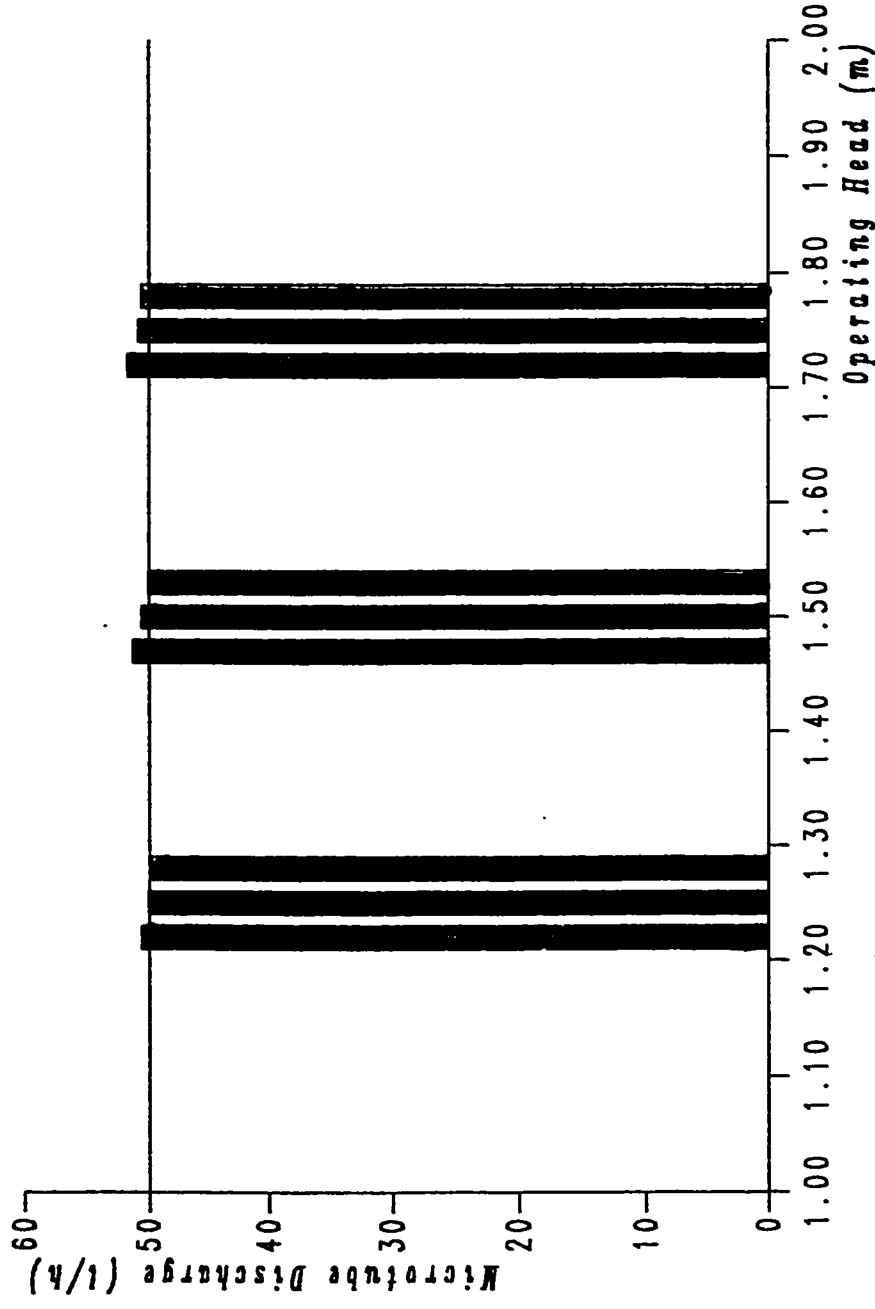


Figure (4.12) Experimental Values of the Microtube Discharge for (3.0 mm) Microtube Diameter

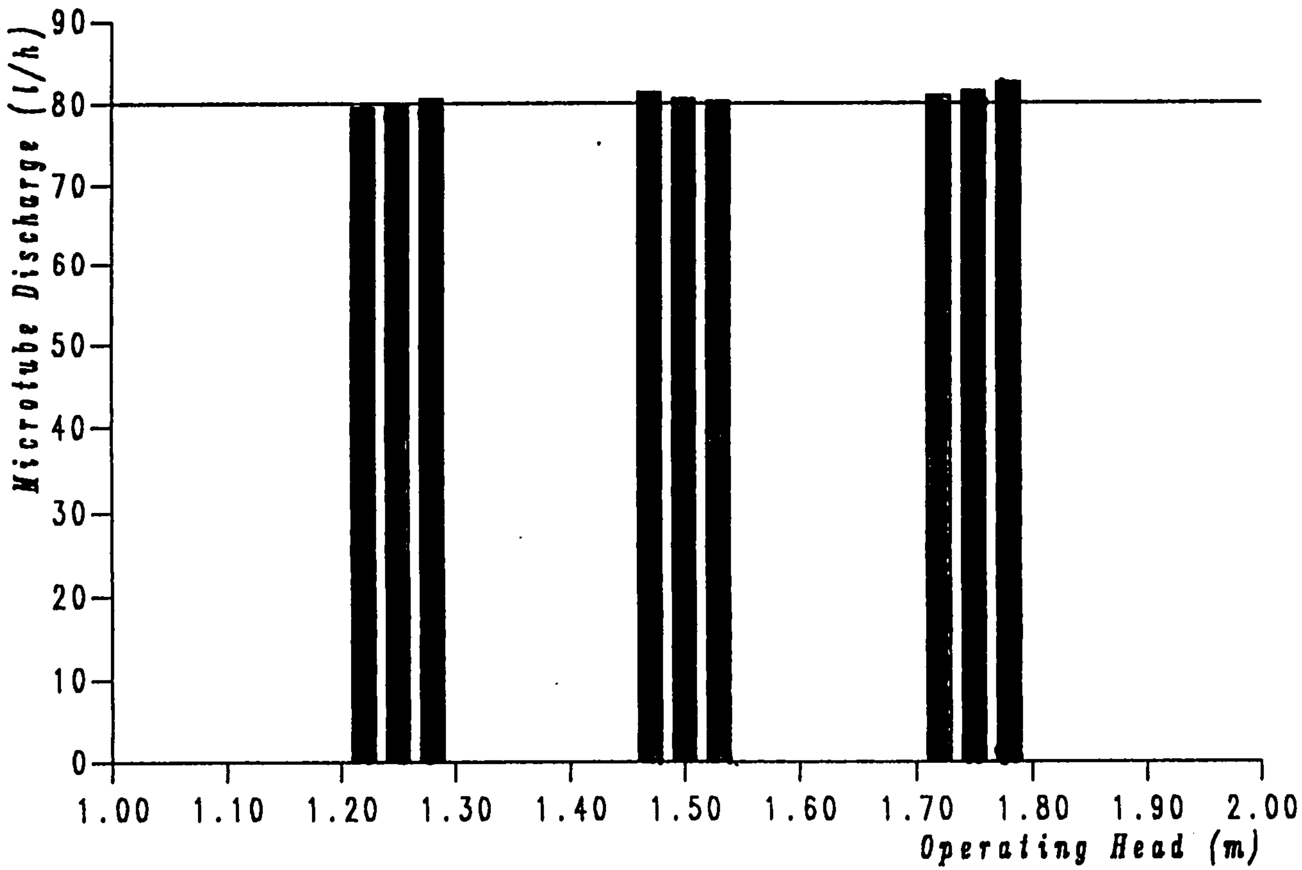


Figure (4.13) Experimental Values of the Microtube dischage for (3.8 mm) Microtube Diameter

CHAPTER 5

DESIGN OF MAIN AND SUBMAINS USING LINEAR PROGRAMMING

5.1 GENERAL BACKGROUND

5.1.1 Operation Research

Operation research (OR) seeks the determination of the best (optimum) cause of action of a decision (variables) problem under various restiricions. (OR) begins with the description of the problem by a model, and then manipulation of the model to find the best way of operating the system (42,43).

It is necessary for any (OR) study to formulate objectives concisely and clearly. After formulating the problem, the next step is to construct the model for the problem. In (OR) work this is usually a mathematical model, which includes variables, objective function and constraints (43).

Variables: The identification of possible variables represents a crucial aspect of the decision process. It entails identifying the variables of the system that are under the control of the decision maker (42).

Objective Function: The objective function is a mathematical function of the variables, and an optimal solution is attained when values for the variables yield the best value of the objective function. A common

objective in money-making endeavours is to maximize profits and minimize costs (44).

Constraints: The variables of a model are usually restricted to feasible range of values, because of the technological and economic limitations of the real life system. Constraints are imposed on the objective function depending on the type of the problem to satisfy the problem conditions (42).

The solution of the model is an optimizing technique and tend to be, but not exclusively, iterative procedure as, for example, the simplex algorithm of linear programming (44).

Linear programming is concerned with maximization (or minimization) linear objective function, subject to satisfaction of other linear relationships (constraints). The technique of linear programming has been applied effectively to many diverse problems (42).

5.1.2 Zero-One Implicit Enumeration

Any integer variable can be equivalently expressed of number of zero-one (binary) variables. The simplest way to accomplish this, is as follows:

Let $0 \leq X \leq n$ be an integer variable, where (n) is an integer upper bound. Then, given that $y_1, y_2, \ldots\ldots y_n$ are zero-one variables, the variable (X) can be expressed as:

$$X = y_1 + y_2 \ldots\ldots + y_n$$

when a real variable (X) takes only a single value from specific known real values $x_1, x_2, \ldots\ldots x_n$ and given that $y_1, y_2, \ldots\ldots y_n$ are zero-one variables

$$X = x_1 y_1 + x_2 y_2 + \ldots\ldots + x_n y_n$$

From the above equation the variables (X) will have a value of either one of the given values $x_1, x_2, \ldots x_n$ or the summation of all the possible combinations between the values (42).

To specify only a single value of the known values to the variable (X), another constraint will be added to force all the zero-one variables to be zeros except for only one value. This constraint is as follows

$$y_1 + y_2 + \ldots + y_n = 1$$

5.1.3 Optimum Design of a Pipe with Constant Discharge

Ofen (4) presented linear programming model that can be used to design an optimum pipe. The model assumes that the discharge and the operating head at the pipe inlet have already been determined. The total head at the pipe outlet and the microtube discharge depend on the design recommendations. It is required to determine the optimum pipe diameters segments to satisfy the head at the pipe outlet .

1 - Objective function

The objective function in the problem in hand is to minimize the pipe cost. Usually pipe cost is proportional to the pipe diameter, where increaseing the pipe diameter leads to increase in pipe cost.

Assume that a pipe with diameter (D_i) has a cost per unit length of (c_i). Figure 5.1 shows the pipe segment of the pipe and their corresponding diameters (D_i) and lengths (X_i). The cost along X_i is therefore $c_i * X_i$. It follows that the cost total (C) along the pipe section is computed from :

$$C = \sum_{i=1}^{N} (c_i X_i) \qquad (5.1)$$

where

C = total cost of the pipe

N = number of used diameters

c_i = cost per unit length of the pipe segment (i)

x_i = length of the pipe segment (i)

The objective of the design is to minimize the total cost of the pipe which can be expressed by the following equation:

$$\text{Min } C = \sum_{i=1}^{N} (c_i X_i) \qquad (5.2)$$

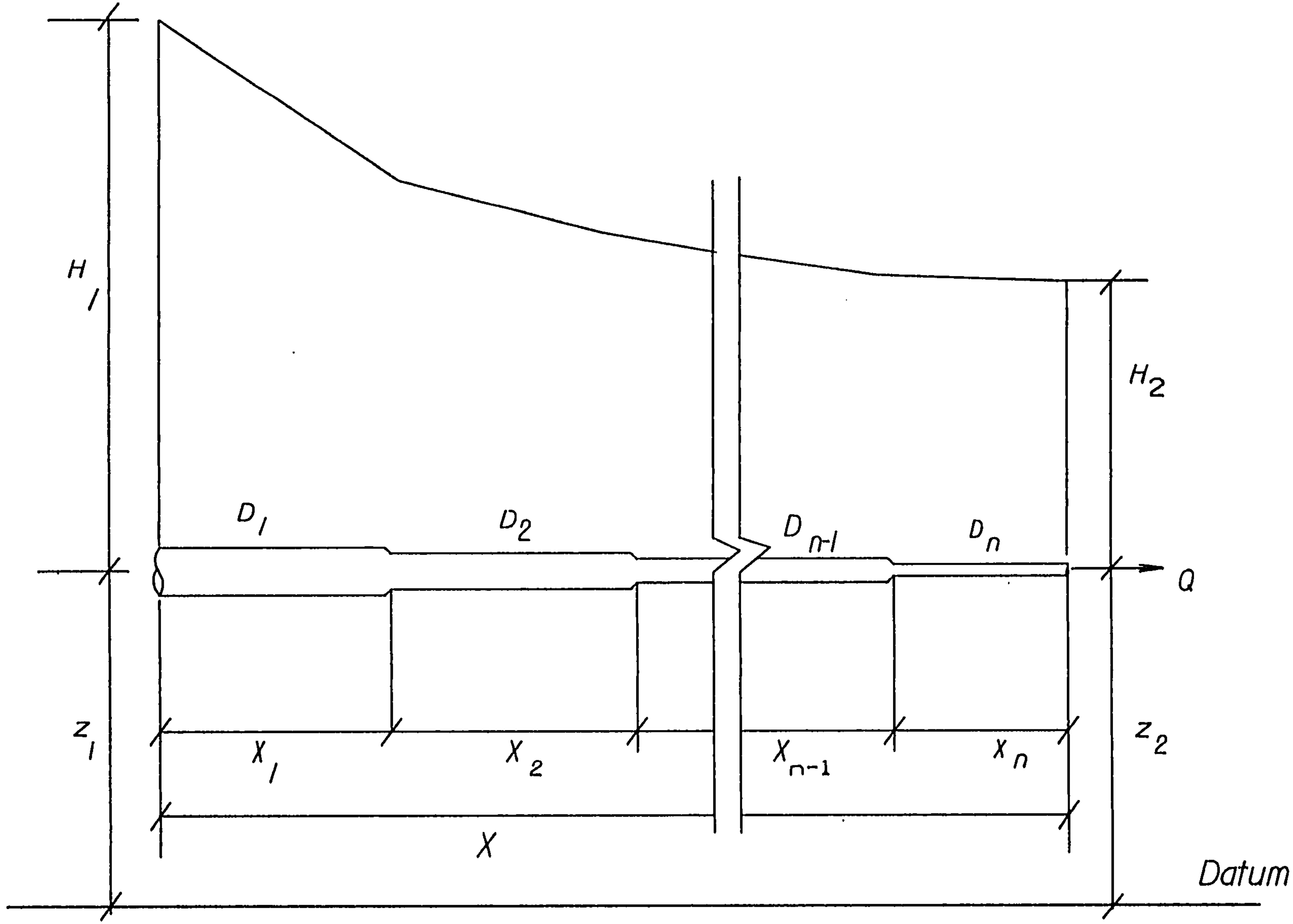


Figure (5.1) Pipe Segments and Total Energy Line

2 - Constraints

In the present model, there are three constraints. The first constraint is concerned with the requirement of the pressure head at the end of the pipe (H_2) which should be at least

$$H_2 = H_1 - Z - \sum_{i=1}^{N} h_{f_i} \qquad (5.3)$$

Where

H_2 = total head at the pipe outlet

H_1 = total head at the pipe inlet

Z = difference in elevation between the pipe ends

= S * X

S = land slope (+ ve upward & - ve downward)

X = total pipe length

h_{f_i} = head loss along the pipe (i)

= $J_i * X_i$

J_i = head loss per unit length of a pipe having a diameter D_i. (m/m) J_i can be computed depending on the suitable friction equation.

The second constraint in the model states that in each pipe section (i) the sum of the partial pipe lengths having diameter (D_i) equals the total length (X) thus:

$$\sum_{i=1}^{N} X_i = X \qquad (5.4)$$

The third constraint involves the non-negativity of various linear programming decision variables , i.e. the pipe-lengths :

$$X_i \geq 0 \qquad (5.5)$$

The objective function and the associated constraints form a linear programming model, which can be solved by means of an appropriate computer program.

5.2 OPTIMUM PIPES NETWORK

Several design procedures have been developed for main and submain design, but they do not guarantee that the solution has the lowest cost, although they satisfy the design requirements. There are many variables affecting the optimality of the model, however, they are very difficult to be formulated in the model. This difficulty is because they may be very complex, unpredictable, vary from one site to another site, dependent on the designer wishes or dependent on the availability of funds with time. Examples of such variables are operating and maintenance costs.

In the model in hand, the initial cost will only be formulated in an optimization model and solved for optimum, however, other variables will be left for the designer to select the suitable choice depending on the

objective and the design conditions.

Trickle irrigation pipe network consists of main, submains and laterals. Laterals are always of the same diameter for the whole network, which is easier to be designed separatly. The procedure will take into account a network consisting of a main and submains. Figure 5.2 shows one of the systems of main and submains network, where each node indicates a lateral intake. The system consists of a pump station, main and submains. An optimization technique will be used to determine the optimum pump and the pipe diameters to minimize their capital costs. The number of diameters used in the system depends on the market availability and the designer experience.

Assume the submain number is (i), the lateral number is (j) and the pipe diameter number is (k)

Where

$i = 1,2,......M$

$j = 1,2,......N$

$k = 1,2,......P$

M = number of submains

N = number of laterals

P = number of used diameters

Each node is defined by the subscript (i,j) where (i) indicates the submain number and (j) indicates the lateral number. The pipe

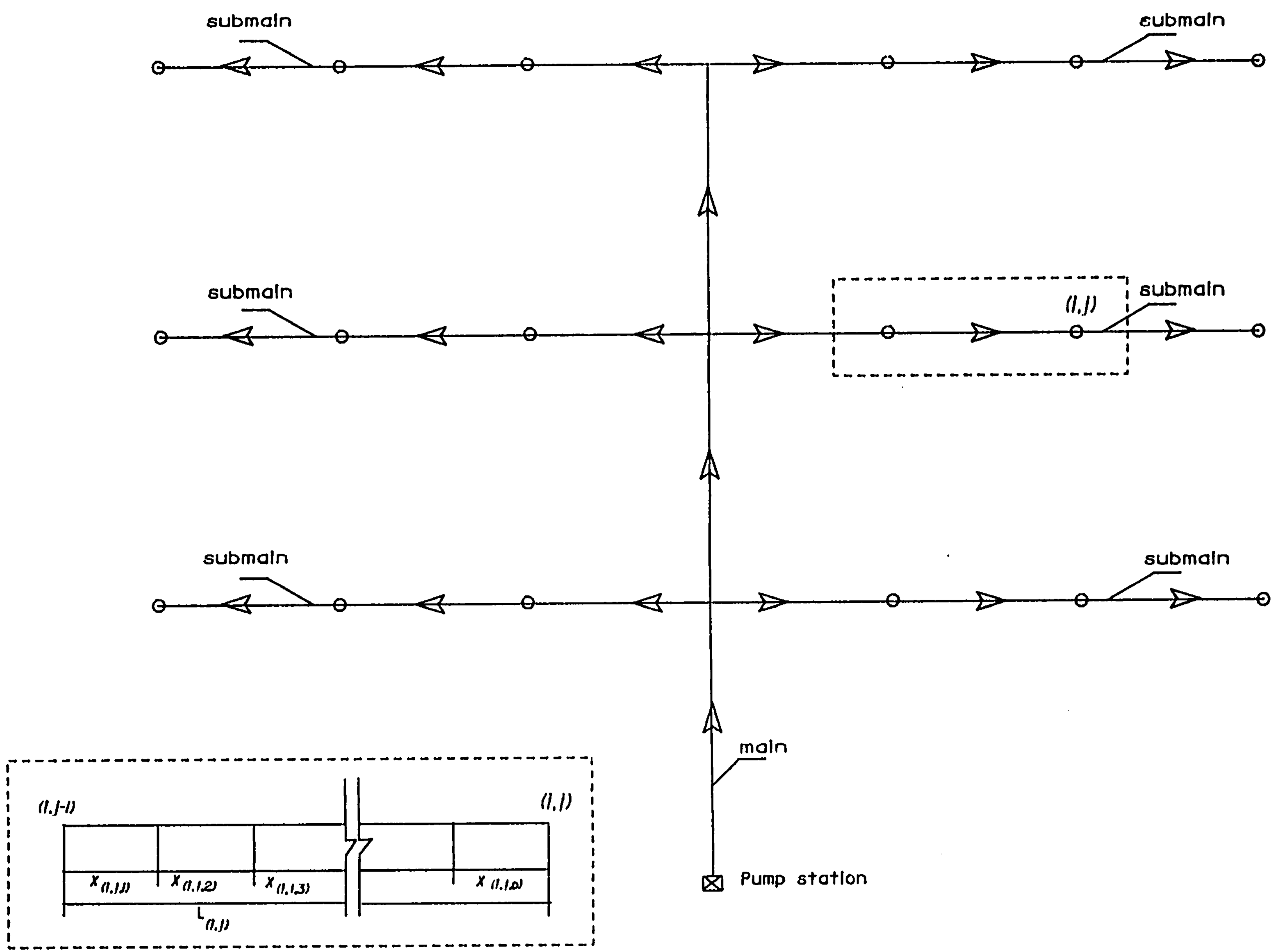


Figure (5.2) Layout of Submains and Main Network

segments between any two nodes is defined by the subscript $X_{(i,j,k)}$, where (k) indicates the pipe diameter. The pipe diameter is also defined by $D_{(i,j,k)}$ to specify the location of the used diameter. The cost per unit length of the pipe $X_{(i,j,k)}$ with pipe diameter $D_{(i,j,k)}$ is expressed by $c_{(i,j,k)}$.

5.2.1 Objective Function

1 - Pipes costs

The total pipe cost for the whole network (C') is the summation of all pipe segment costs, which can be expressed by the following equation:

$$C' = \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{P} (c_{(i,j,k)} * X_{(i,j,k)}) \qquad (5.6)$$

The objective function of the pipes is to minimize the total pipe costs for the whole network which is:

$$\text{Min } C' = \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{P} (c_{(i,j,k)} * X_{(i,j,k)}) \qquad (5.7)$$

2 - Pump cost

Different pumps provide different operating heads, discharges, operating cost and maintenance cost. The proper design of pumps is an integral part of the design of piping system. Selection of the pump

is based on the needed quantity of discharge and total head. For the same pump the total head developed is inversely proportional with the delivered discharge, but at a specific discharge, the pump develops single value for the total head. Figure 5.3 shows the shape of a typical pump curve relating the developed total head and the delivered discharge (27). So the problem becomes the determination of the head which minimizes the the pipe cost combined with pump cost.

Assume that the designer chooses different pumps which provide the same discharges and their corresponding costs are C_1 , C_2 ......C_r. At the given discharge, the chosen pump provides different total heads H_1 , H_2 ......H_r. It is aimed to specify only one pump, which satisfies the optimality of the system. The total pump cost (C") is expressed by the following equation:

$$C'' = C_1\ y_1 + C_2\ y_2 \ .... \ C_r\ y_r \qquad (5.8)$$

Where

$$y_1 + y_2 \ .... \ y_r = \text{zero-one variables}$$

The objective function of the pump is:

$$\text{Min} \sum_{i=1}^{r} C'' = (\ C_i\ y_i\ ) \qquad (5.9)$$

As mentioned earlier in zero-one technique, Equation (5.9) will have only single solution for the optimum, where a single value of (y_i) is

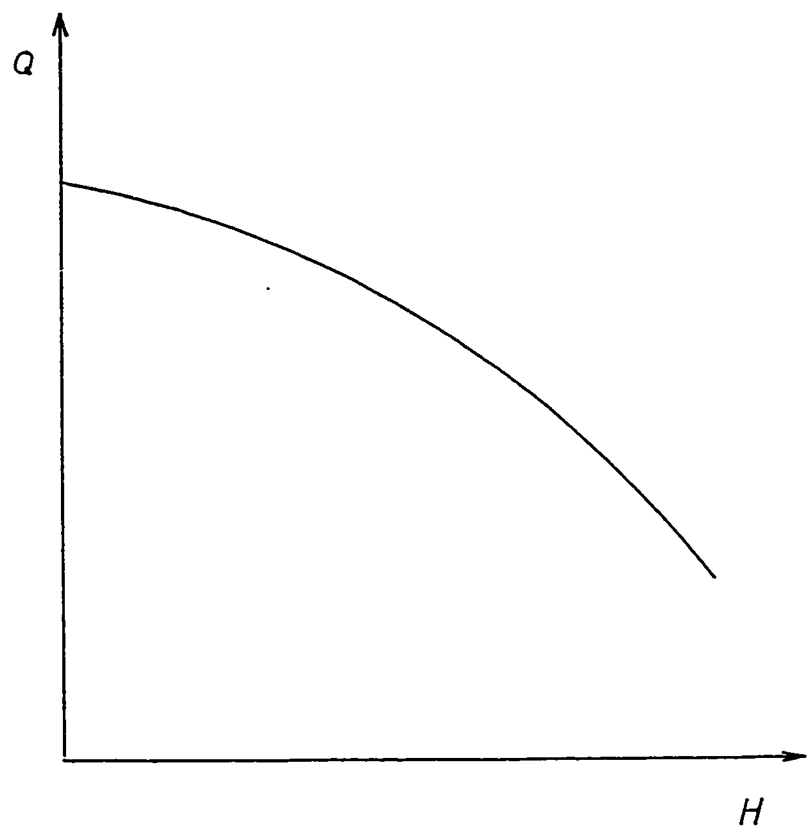


Figure (5.3) Typical Shape of Q - H Relatioship for a Pump

unity (denoted as (y_t)) and all other values of (y_i) are equal to zero.

From Equations (5.7) and (5.9) the objective function of network (C) is expressed as:

$$\text{Min } C = \sum_{i=1}^{r} (c_{(i,j,k)} * X_{(i,j,k)}) + \sum_{i=1}^{r} C_i * y_i \qquad (5.10)$$

5.2.2 Constraints

1 - Length constraint

The sum of the pipe lengths with all possible diameters between any two nodes must be equal to the length between the two nodes.

$$\sum_{k=1}^{P} X_{(i,j,k)} = L_{(i,j)} \qquad (5.11)$$

Where

$L_{(i,j)}$ = length of a pipe between (i,j) and (i,j+1) nodes

2 - Zero-one constraint

The sum of all zero-one variables must be equal to a value of one in order to specify a single pump for the network.

$$y_1 + y_2 + \ldots\ldots . y_r = 1 \qquad (5.12)$$

3 - Pump total head constraint

The pump total head (H) is considered as one of the variables,

which is determined after selecting the optimum pump. This concept is expressed by the following equation:

$$H = H_1\ y_1 + H_2\ y_2 + \ldots\ldots H_r\ y_r \qquad (5.13)$$

4 - **Network total heads constraint**

The total head at the lateral inlet (network nodes) should satisfy the lateral total head recommendations which may be within certain limits of total heads or a percentage of the average total head throughout the network. The total head loss from the pump station up to the node consists of:

a - Friction head loss

Friction head loss from the pump station through the water path to the node which is expressed as:

$$\sum_{i=1}^{N} \sum_{j=1}^{M} \sum_{k=1}^{P} J_{(i,j,k)} * X_{(i,j,k)} \qquad (5.14)$$

Where

J = head loss per unit length of the pipe segment (i,j,k)

$X_{(i,j,k)}$ = length of the pipe segment (i,j,k)

b - Head loss (or gain) due to change in elevation

The difference in elevation (Z) between the pump and the node (i,j,k) can be calculated from the pipe lengths and their slopes.

$$Z = \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{P} (S_{(i,j,k)} * X_{(i,j,k)}) \qquad (5.15)$$

Where

$S_{(i,j,k)}$ = the slope of pipe segment $X_{(i,j,k)}$

Hint: entrance and connection losses will be considered later.

The total head at any node ($h_{(i,j)}$) can be calculated by subtracting the total head loss up to the node from the pump total head. The total head at any node ($h_{(i,j)}$) can be calculated as follows:

$$h_{(i,j)} = H - \left(\sum_{i=1}^{N} \sum_{j=1}^{M} \sum_{k=1}^{P} (J_{(i,j,k)} * X_{(i,j,k)}) - Z \right) \quad (5.16)$$

As an example; if the total head at the lateral inlet ($h_{(i,j)}$) should have an average value (w) with a 10% maximum variation, $h_{(i,j)}$ is expressed as follows:

$$0.9\ w \le h_{(i,j)} \le 1.1\ w$$

$$0.9\ w \le H - \left(\sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{P} (J_{(i,j,k)} * X_{(i,j,k)} - Z \right) \le 1.1\ w$$

or

$$H - \left(\sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{P} (J_{(i,j,k)} * X_{(i,j,k)}) - Z \right) \le 1.1\ w$$

$$H - \left(\sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{P} (J_{(i,j,k)} * X_{(i,j,k)}) - Z \right) \ge 0.9\ w$$

5 - Practical pipe arrangement constraint

Practically water should flow through a pipe from larger diameters to smaller diameters, thus the smallest used diameter in any pipe segment must be greater than or equal to the largest diameter in the downstream pipe segment. A constraint will be added to prevent this confliction to choose either the small diameters in the pipe segment or the large diameter in the downstream segment.

Zero-one variables is assumed for each pipe segment. The variable $y_{(i,j,k)}$ is equal to a value of one when the pipe diameter is used and equals to zero when it is not used. This can be formulated by the following constraint:

$$x_{(i,j,k)} \leq L_{(i,j)} * y_{(i,j,k)} \qquad (5.17)$$

To prevent the confliction between any two nodes, a constraint will be added to the model as follows:

$$y_{(i,j,k)} + y_{(i,j,k+s)} = 1 \qquad (5.18)$$

The value of $(k+s)$ indicates large diameter than the diameter (k). The value of (s) changes from a value equals to one to a value equals to $(n-k)$.

6 - The Non-negative length constraint

Any segment length must be equal to or greater than zero

$X_{(i,j,k)} \geq 0$

For $i=1,2......M$

$j=1,2......N$

$k=1,2......P$

5.3 Application on the Design of Main and Submains Using Computer Programming

Optimization techniques can be used in any pipe network but the designer must have the knowledge of the market pipe prices. The designer should also have the experience to choose the appropriate operating pump heads and their costs. The most important constraint to be known by the designer is the total head distribution throughout the network.

For example; if the designer is supposed to design the network shown in Figure 5.4, to keep the head at the nodes between 6.0 to 9.0 m and the lateral discharge is 24 m^3/h, three pipe diameters of 75, 100, and 150 mm are to be used in the submains. Table 5.1 shows the (J) values for the three submain diameters for different delivered discharges. Four pipe diameters of 100, 150, 200, and 250 mm are to be used in the main. Table 5.2 shows the (J) values for the four main diameters for the different delivered discharges.

The pipe costs are 107, 130, 207, and 350 SR per meter for the 100, 150, 200 and 250 mm pipes, respectively.

Operating head (cm)	pipe diameter (mm)		
	100	150	200
24	7.8	1.1	0.25
48	28.0	4.0	1.0
72	60.0	8.3	2.0

Table 5.1 Values of j (‰) for submains pipe segments

Operating head (cm)	pipe diameter (mm)			
	100	150	200	250
72	60.0	8.3	2.0	--
144	--	33.2	8.0	2.62
216	--	74.0	18.0	5.9

Table 5.2 Values of j (‰) for main pipe segments

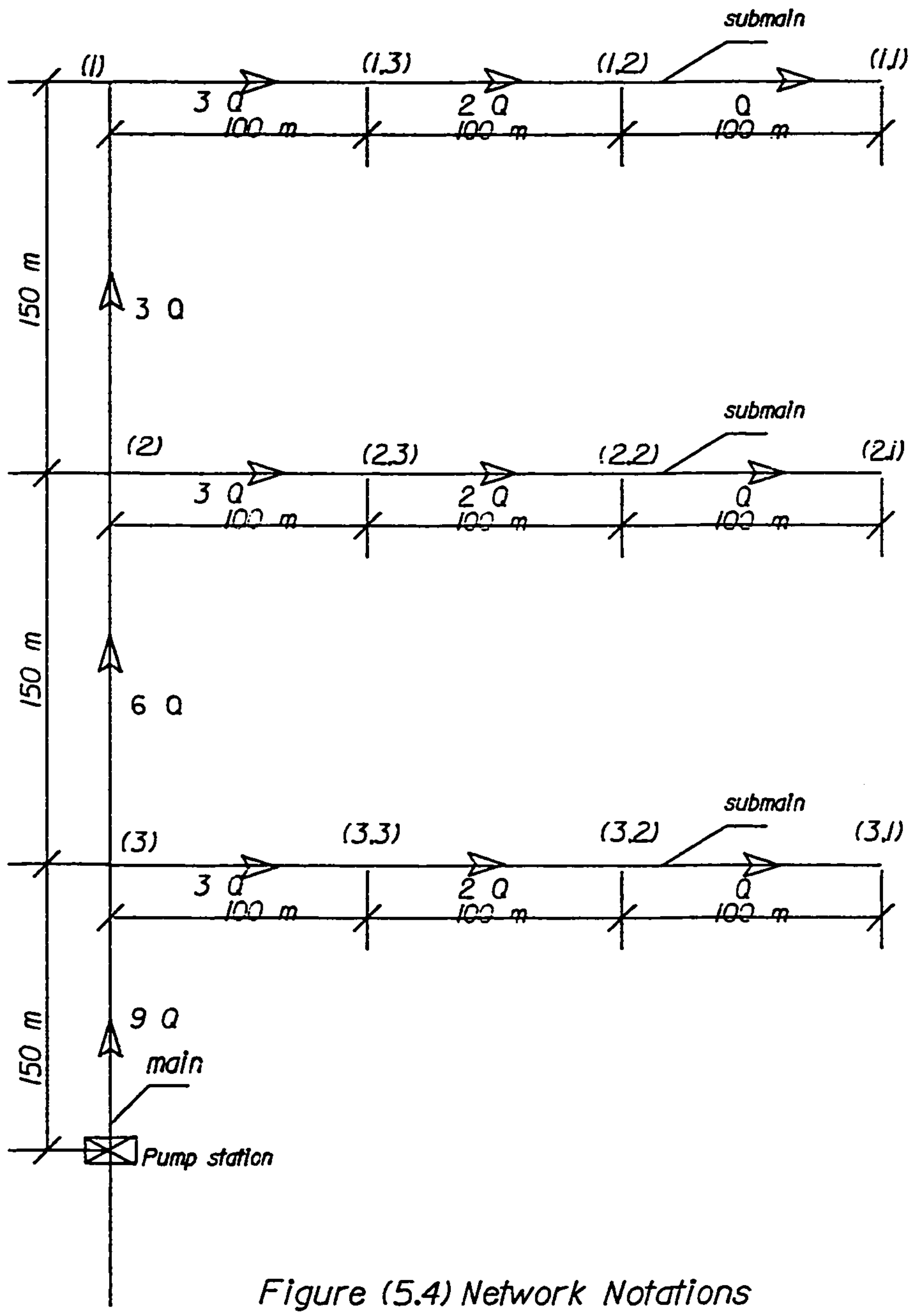


Figure (5.4) Network Notations

It is recommended to use 4 pumps with 10, 13, 16, and 17 m operating total head. Their costs are 100,000, 121,000, 144,000, and 169,000 SR; respectively. The pipe segment and nodes notations are shown in Figure 5.5.

5.3.1 Problem Formulation

a - Objective Function

1- pipe cost

```
min    107 x111 + 130 x112 + 207 x113
     + 107 x121 + 130 x122 + 207 x123
     + 107 x131 + 130 x132 + 207 x133
     + 107 x211 + 130 x212 + 207 x213
     + 107 x221 + 130 x222 + 207 x223
     + 107 x231 + 130 x232 + 207 x233
     + 107 x311 + 130 x312 + 207 x313
     + 107 x321 + 130 x322 + 207 x323
     + 107 x331 + 130 x332 + 207 x333
     + 130 x31  + 207 x32  + 350 x33
     + 130 x21  + 207 x22  + 350 x23
     + 107 x11  + 130 x12  + 207 x13
```

2- pump cost

```
     + 100000.0 y1 + 121000.0 y2
     + 144000.0 y3 + 169000.0 y4
```

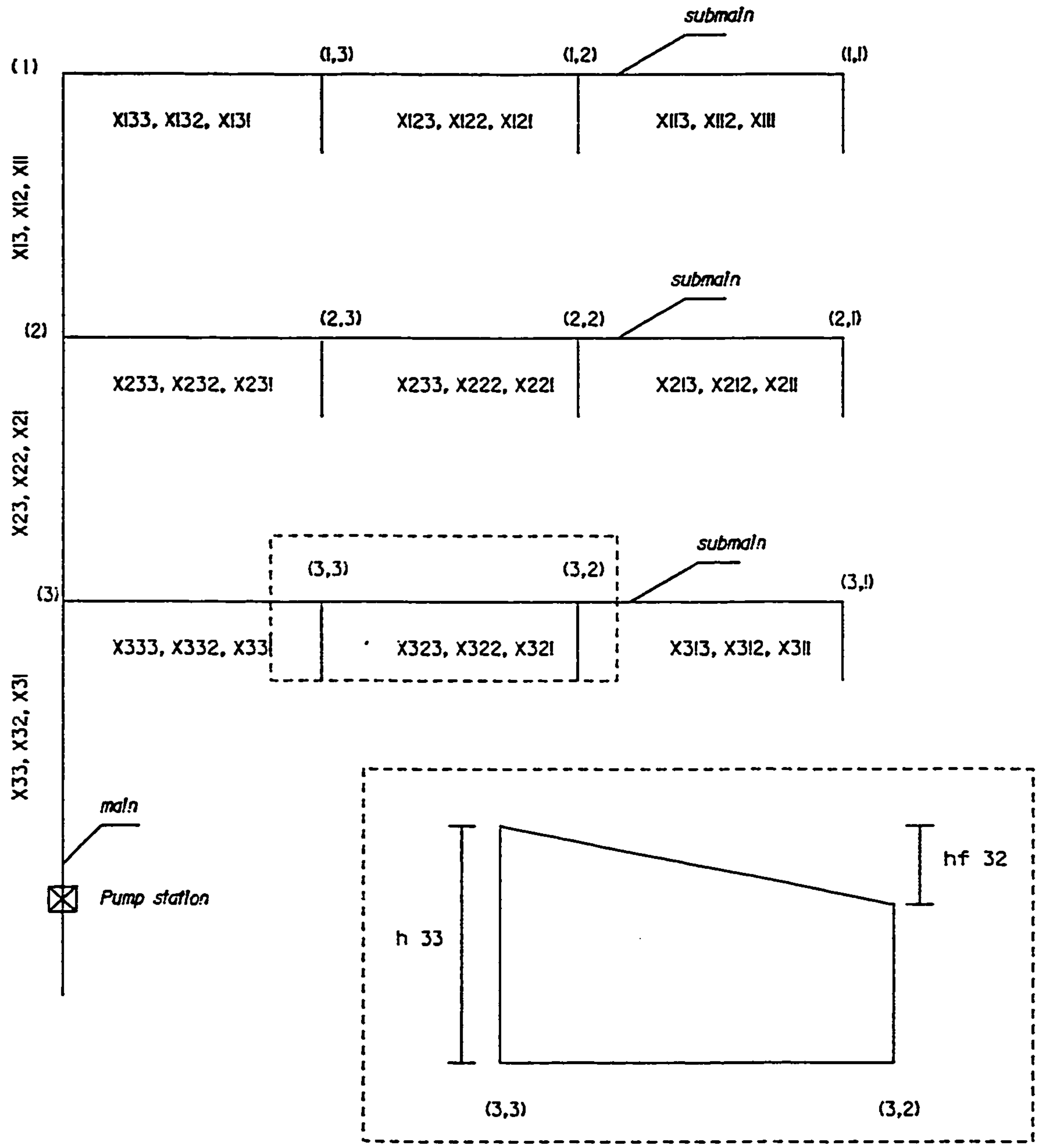


Figure (5.5) Nodes and Pipes Notations

b- Constraints

1- pump pressure head constraint

2) $y1 + y2 + y3 + y4 = 1$

2- length constraints

3) $x111 + x112 + x113 = 100$
4) $x121 + x122 + x123 = 100$
5) $x131 + x132 + x133 = 100$
6) $x211 + x212 + x213 = 100$
7) $x221 + x222 + x223 = 100$
8) $x231 + x232 + x233 = 100$
9) $x311 + x312 + x313 = 100$
10) $x321 + x322 + x323 = 100$
11) $x331 + x332 + x333 = 100$
12) $x31 + x32 + x33 = 150$
13) $x21 + x22 + x23 = 150$
14) $x11 + x12 + x13 = 150$

3- pump total head calculation

15) $10000y1+13000y2 + 16000y3 + 17000y4 - h0 = 0$

4- total head requirements constraints

```
16) 74x31+18.0x32+5.90x33 - hf3 = 0
17) h0-hf3>=7000
18) h0-hf3<=20000
19) 33.2x21+8.0x22+2.62x23-hf2= 00
20) h0-hf3-hf2<=20000
21) h0-hf3-hf2>=7000
22) 60.0x11+8.3x12+2.0x13 - hf1 =00
23) h0-hf3-hf2-hf1>= 7000
24) h0-hf3-hf2-hf1<= 20000
25) 60.0x331+8.3x332+2.0x333 - hf33 =000
26) h0-hf3-hf33>=6000
27) h0-hf3-hf33<=9000
28) 28.0x321+4.0x322+1.0x323 - hf32 =000
29) h0-hf3-hf33-hf32>=6000
30) h0-hf3-hf33-hf32<=9000
31) 7.80x311+1.1x312+0.25x313 - hf31 =000
32) h0-hf3-hf33-hf32-hf31>=6000
33) h0-hf3-hf33-hf32-hf31<=9000
34) 60.0x231+8.3x232+2.0x233 - hf23 =000
35) h0-hf3-hf2-hf23>=6000
36) h0-hf3-hf2-hf23<=9000
37) 28.0x221+4.0x222+1.0x223 - hf22 =000
38) h0-hf3-hf2-hf23-hf22>=6000
39) h0-hf3-hf2-hf23-hf22<=9000
40) 7.80x211+1.1x212+0.25x213 - hf21 =000
41) h0-hf3-hf2-hf23-hf22-hf21>=6000
42) h0-hf3-hf2-hf23-hf22-hf21<=9000
43) 60.0x131+8.3x132+2.0x133 - hf13 = 0
44) h0-hf3-hf2-hf1-hf13>=6000
45) h0-hf3-hf2-hf1-hf13<=9000
46) 28.0x121+4.0x122+1.0x223 - hf12 = 000
47) h0-hf3-hf2-hf1-hf13-hf12>=6000
48) h0-hf3-hf2-hf1-hf13-hf12<=9000
49) 7.80x111+1.1x112+0.25x113 - hf11 =000
50) h0-hf3-hf2-hf1-hf13-hf12-hf11>=6000
51) h0-hf3-hf2-hf1-hf13-hf12-hf11<=9000
```

5- pipe arrangement constraints

```
53) x112 - 100 y112<=0
54) x121 - 100 y121<=0
55) x122 - 100 y122<=0
56) x131 - 100 y131<=0
57) x132 - 100 y132<=0
59) x212 - 100 y212<=0
60) x221 - 100 y221<=0
61) x222 - 100 y222<=0
62) x231 - 100 y231<=0
63) x232 - 100 y232<=0
65) x312 - 100 y312<=0
66) x321 - 100 y321<=0
67) x322 - 100 y322<=0
68) x332 - 100 y332<=0
69) x113 - 100 y113<=0
70) x123 - 100 y123<=0
71) x133 - 100 y133<=0
72) x213 - 100 y213<=0
73) x223 - 100 y223<=0
74) x233 - 100 y233<=0
75) x331 - 100 y331<=0
76) x313 - 100 y313<=0
77) x323 - 100 y323<=0
78) x333 - 100 y333<=0
79) y112+y121<=1
80) y113+y121<=1
81) y113+y122<=1
82) y122+y131<=1
83) y123+y131<=1
84) y123+y132<=1
85) y212+y221<=1
86) y213+y222<=1
87) y213+y221<=1
88) y222+y231<=1
89) y223+y231<=1
90) y223+y232<=1
91) y312+y321<=1
92) y313+y321<=1
93) y313+y322<=1
94) y322+y331<=1
95) y323+y331<=1
97) x12 - 150 y12 <= 0
98) x13 - 150 y13 <= 0
99) x21 - 150 y21 <= 0
100)x22 - 150 y22 <= 0
```

```
101)x23 - 150 y23 <= 0
102)x31 - 150 y31 <= 0
103)x32 - 150 y32 <= 0
104)x33 - 150 y33 <= 0
104)y12+y21<=1
105)y13+y21<=1
106)y13+y22<=1
107)y22+y31<=1
108)y23+y31<=1
109)y23+y32<=1
110)h0-hf3-h3=0
```

6- pressure head calculations

```
111)h0-hf3-hf2-h2=0
112)h0-hf3-hf2-hf1-h1=0
113)h0-hf3-hf33-h33=0
114)h0-hf3-hf33-hf32-h32=0
115)h0-hf3-hf33-hf32-hf31-h31=0
116)h0-hf3-hf2-hf23-h23=0
117)h0-hf3-hf2-hf23-hf22-h22=0
118)h0-hf3-hf2-hf23-hf22-hf21-h21=0
119)h0-hf3-hf2-hf1-hf13-h13=0
120)h0-hf3-hf2-hf1-hf13-hf12-h12=0
121)h0-hf3-hf2-hf1-hf13-hf12-hf11-h11=0
```

The problem described above was solved using 'Lindo' a program on the personal computer. Figure A.14a in Appendix A shows the problem formulation and Figure A.14b shows the computer output.

CHAPTER (6)

SUMMARY AND CONCLUSION

1 - For trickle irrigation systems design charts and nomographs as well as a computer program have been developed to determine the length of the microtubes required to deliver equal amount of water in the case of microtubes with and without coils.

2 - Experimental study showed slight increase in the amount of discharge than that obtained by chart and theory. This error may be due to cross-sectional variations of the microtubes during manufacture or in the hydraulic relationships that needs to be investigated further.

3 - Although there was a slight discrepancy between the calculated and the experimental values of microtube discharges (with in acceptable limits), the discharges in the network itself were uniform.

4 - A computer program has been developed to determine the parameters for the design of laterals using the developed computer program.

5 - Experimental study showed good agreement with the theory for the design of laterals.

6 - Considering the cost of the network, optimization techniques have been used to minimize the cost of main, submains and pumping station while satisfying the design requirements.

REFERENCES

1 - I. Vermeirn and G. A. Jobling, "*Localized Irrigation*"., FAO, 1980.

2 - V. E. Hansen, O. W. Israelsen and G.E. Stringham., "*Irrigation Principles and Practices*"., John Wiley and Sons, Inc. 1979.

3 - L. J. Booher, "*Surface Irrigation*"., FAO, 1980.

4 - Benami A. Ofen, "*Irrigation Engineering*"., Irrigation Engineering Publications (IESP), 1984.

5 - V. F. Bralts and I. P. Wu, "*Emitter Flow Variation and Uniformity for Drip Irrigation*"., (ASAE Technical Paper No. 79-2015) presented at the 1979 summer meeting of ASAE and CSAE, Manitoba, Winnipeg, June 24-27, 1979.

6 - Roland P. Perold, "*Design of Irrigation Pipe Laterals with Multiple Outlets*"., J.I.D.D. Vol. 103, No. IR2. June 1977, pp 179 - 195.

7 - I-Pai Wu and Harris M. Gitlin, "*Design of Drip Irrigation Submain*"., J.I.D.D. Vol. 103, No. IR2. June 1977, pp 231 - 243.

8 - I-Pai Wu, "*Design of Drip Irrigation Main Lines*"., J.I.D.D. Vol. 101, No. IR4. June 1975, pp 265 - 279.

9 - J. M. Myers and D. S. Harrison, "*Drip Irrigation of Orange Tree in Humid Climate*"., (ASAE Technical Paper No. 78-2018) presented at the 1978 summer meeting of ASAE Logan, Utah, June 27-30, 1978.

10- J. L. Chesness, "*Peach Tree Response to Drip Application* of Water and Nutrients"., (ASAE Technical Paper No. 78-2019) presented at

the 1978 summer meeting of ASAE Logan, Utah, June 27-30, 1978.

11- T. W. Sammis and Eldon G. Hansen, "*Potato and Lettuce Response to Irrigation Methods and Practices*"., (ASAE Technical Paper No. 78-2020) presented at the 1978 summer meeting of ASAE Logan, Utah, June 27-30, 1978.

12- J. E. Middleton, E. L. Proebsting and s. Roberts, "*Apple Tree Irrigation. Trickle vs. Sprinkler*"., (ASAE Technical Paper No. 79-2112) presented at the 1979 summer meeting of ASAE and CSAE, Manitoba, Winnipeg, June 24-27, 1979.

13- L. B. Spiess, "*Trickle Irrigation of Fruit and Ornmental Trees in a Salin Soils*"., (ASAE Technical Paper No. 79-2113) presented at the 1979 summer meeting of ASAE and CSAE, Manitoba, Winnipeg, June 24-27, 1979.

14- D. S. Ross, C. Funt, B. Goulart, "*Evaluation of Trickle Irrigation in Maryland*"., (ASAE Technical Paper No. 79-2114) presented at the 1979 summer meeting of ASAE and CSAE, Manitoba, Winnipeg, June 24-27, 1979.

15- R. G. Gilbert, F. S. Noaknayama, D. A. Bucks, O.F. French and K. C. Adamson, "*Trickle Irrigation Emitter Clogging and Other Flow Problems* "., Agricultural Water Management. 3, (1980/1981) pp 159 - 178.

16- A. W. Warrick and M. Y. Yitayew, "*Trickle Lateral Hydraulics, I: Analytical Solution*"., J.I.D.D. Vol. 114, No. 2, May 1975, pp 281

- 288.

17- A. W. Warrick and M. Y. Yitayew, "*Trickle Lateral Hydraulics, II: Analytical Solution*"., J.I.D.D. Vol. 114, No. 2, May 1975, pp 289 - 300.

18- Shlomo Pleban, Dov Shachan and Jim Loftis, "*Minimizing Capital Costs of Multi-Outlet Pipelines*"., J.I.D.D. Vol. 110, No. 2, June 1984, pp 165 - 178.

19- Krishanlal C. Khatri, I-Pai Wu, Harris M. Gitlin and Allan L. Phillips, "*Hydraulics of Microtubes*"., J.I.D.D. Vol. 105, No. IR2, June 1979, pp 163 - 173.

20- Julian Pitchford, "*Drip System Emission Uniformity Evaluation by Mathematical Model*"., (ASAE Technical Paper No. 79-2098) presented at the 1979 summer meeting of ASAE and CSAE, Manitoba, Winnipeg, June 24-27, 1979.

21- Solomon, K., "*Manufacturing Variations of Emitters in Trickle Irrigation Systems*"., Paper No. 77-2009, ASAE, 1977.

22- Karmeli, David and Keller, Jack, "*Trickle Irrigation Design. Rain Bird*"., Glendora, California, 1975.

23- Karmeli, David, "*Hydraulic Aspects of the Various Drippers*"., Department of Gricultural Engineering Technion, Haifa, Isreal, 1972.

24- Harry J. Brand and Amin M. Soom, "*Trickle Irrigation Design for Improved Application Uniformity*"., Paper No. 79-2571, ASAE,

1979.

25- Paraqueima, J. R., *dy of some Frictional Characteristics of Small Diameter Tubing Trickle Irrigation Laterals*"., thesis presented thr Utah State University at Lagon, Utah, in partial fulfillment of the requriments of Master in Scince, 1977.

26- Watter G. Z. and Keller J., "*Trickle irrigation Tubing Hydraulics*"., (ASAE Technical Paper No. 78-2015) presented at the 1978 summer meeting of ASAE Logan, Utah, June 27-30, 1978.

27- Andrew L. Simon, "*Hydraulics*"., John Wiley and Sons, Inc. 1986.

28- Ben-Ami, A. and Diskin, M. H., "*Design of Sprinkling Irrigation*"., Technion, Israel Institute of Technology, P. N. 23, 1965.

29- Keller, J., "*Selction of economical Sizes for Sprinkler Irrigation System*"., Trans. ASAE. 8, 1965 pp 180 - 190.

30- Aloperovitz, E. and Shamir, U., "*Design of Optimal Water Distribution System*"., Water Resources. Res. , 13 (6): 1977, pp 885 - 900.

31- Herbert E., "*Hydraulic Design - The Use of Polyplot*"., Imperical Chemical Industries of Australia & New Zealand Ltd., Melborne, Australia, 1971.

32- Wu I-pai and Gitlin H. M., "*Design of Drip Irrigation Lines*"., Tech. Puhl. No. 96, Hawii Agric. Exp. Stat., University of Hawaii, 1974.

33- Karmeli, D. and Peri, C., "*Design Procedure for Sprinkler Lateral*"., Proc. Water Mangement for Irrigation and Drainage. ASCE, Speciality Conference, Reno, NV. 1977.

34- Roland P. Perlod, "*Computer design of microirrigation pipe systems*"., J.I.D.D. Vol. 105, IR4,Dec. 1979, pp 403 - 417.

35- Shlomo Pleban and Ian Amir, "*Design Procedure of Sprinkling Laterals: The Mathimatical Background of a computerized Aid*"., Agricultural Water Mangement, 3 (1980-1981) pp 169 - 278.

35- Wu, I. P. and Gitlin H. M., "*Hydraulics and Uniformity for Drip Irrigation*"., J.I.D.D. Vol. 99, No. IR3, Jun. 1973, pp 157 - 168.

37- Myers, L.E. and Bucks, D. A., "*Uniform Irrigation with Low-pressure Trickle System*"., J.I.D.D. Vol. 98, No. IR3, Sep. 1972, pp 341 - 346.

38- Howell, T.A. and Hiler, E. A., "*Trickle Irrigation Lateral design*"., Transaction, ASAE, Vol. 17, No. 5, Sep. - Oct., 1974, pp 902 - 908.

39- I-Pai Wu and Harris M. Gitlin, "*Design of Drip Irrigation lines with Varying Pipe Sizes*"., J.I.D.D. Vol. 103, No. IR4, Dec. 1977, pp 499 - 503.

40- Lee H. Johson, "*Nomography and Impirical Equations*"., John Wiley and Sons, Inc. 1952.

41- Dale S. Davis, "*Nomography and Impirical Equations*"., Reinhold Publishing Corporation, 1962.

42- Hamdy Taha, "*Operation Research*"., MacMillan Publishing Co. Inc., 1982.

43- J. E. Shamblen and G. T. Stevens, "*Operation Research; Fundamental Aproach*"., McGrew-Hill, Inc., 1974.

44- David Whitaker, "*OR on Micro*"., John Wiley and Sons Ltd. 1984.

APPENDIX A

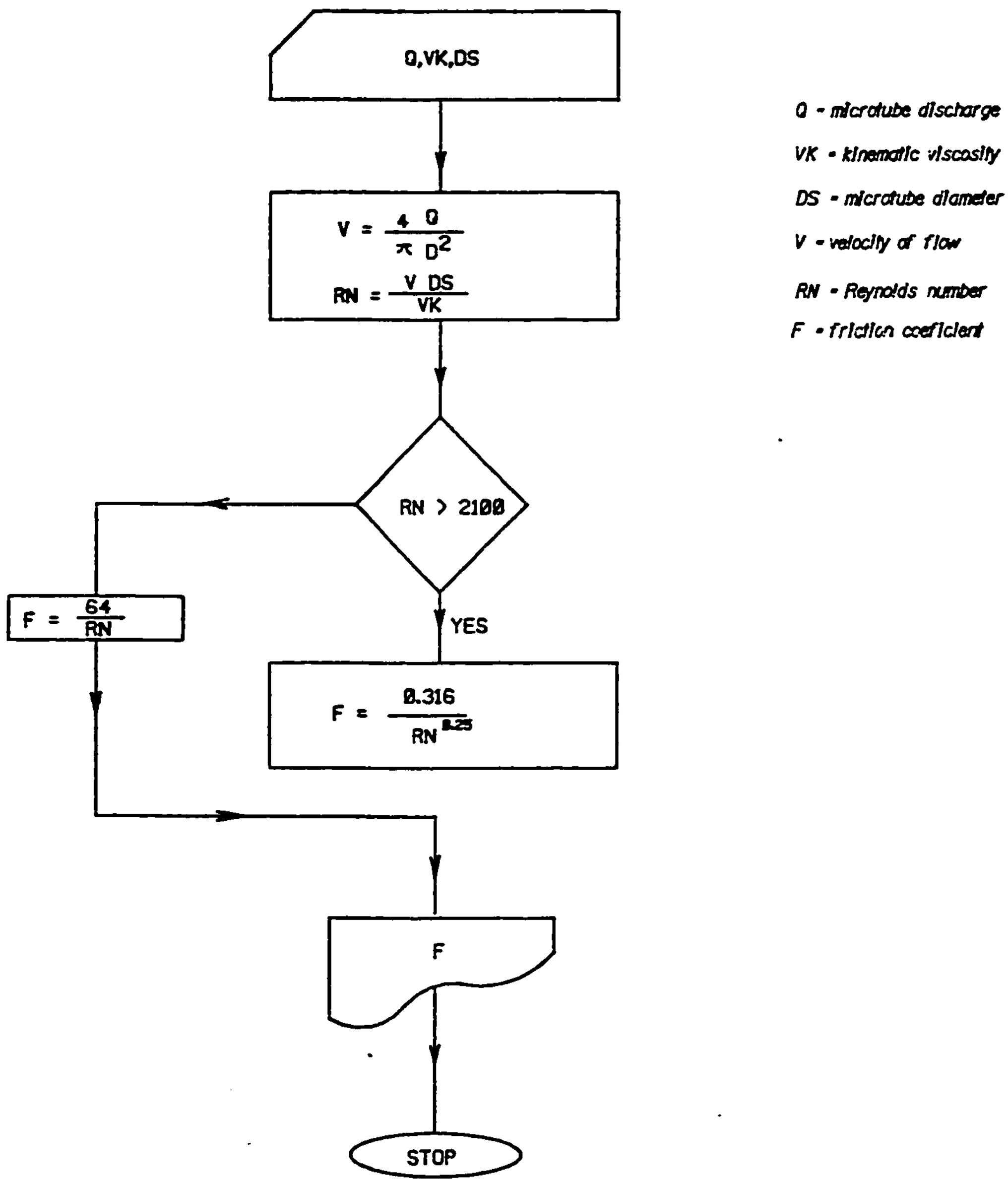
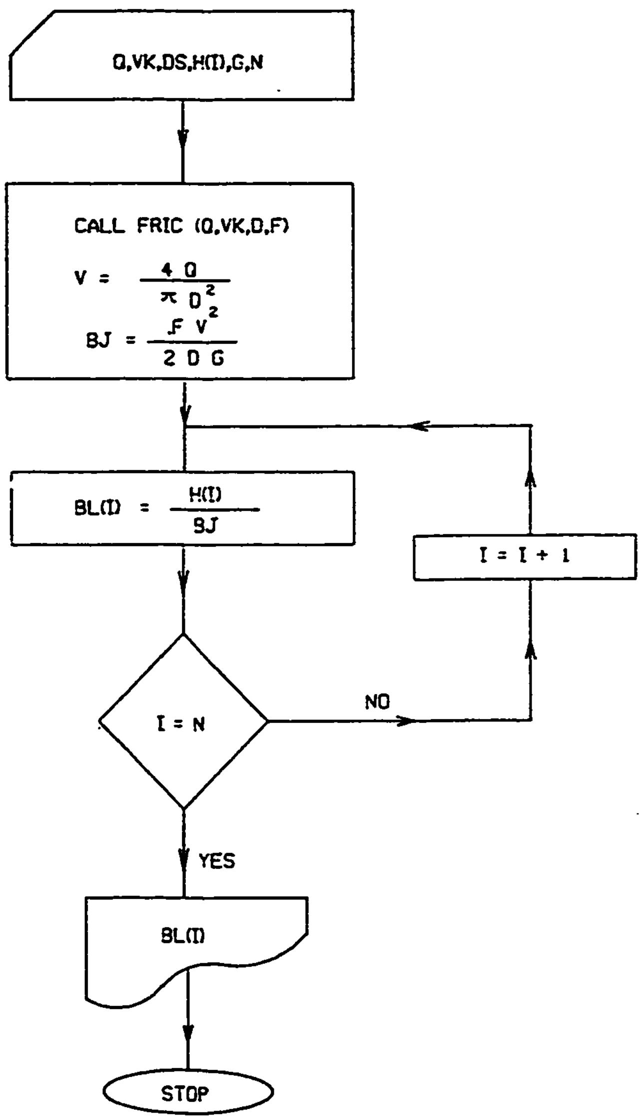


Figure (AI.a) Friction Coeficient in Laminar and Turbulent Flows.

```
C   *****************************************************************
C   * THIS SUBROUTINE CALCULATES THE FRICTION COEFICENT FOR A PIPE.    *
C   *****************************************************************
      SUBROUTINE FRIC(Q,VK,D,F)
      V=(4*Q)/(3.14159*(D**2))
      RN=(V*D)/VK
      IF(RN.GT.2100)GO TO 140
        F=64/RN
         GO TO 150
  140   F=0.316/(RN**0.25)
  150 RETURN
      END
```

Figure (A.1.b) Subroutine for Friction Coefficent Determination



Q - microtube discharge

VK - kinematic viscosity

DS - microtube diameter

H(I) - total head at the microtube (i)

G - specific gravity

N - number of microtubes

V - folw velocity

BJ - friction head loss per unit length

BL(I) - microtube (i) length

Figure (A.2.a) Flow Chart for Microtube Length Without Coils

```
C    ******************************************************************
C    * THIS SUBROUTINE CALCULATES THE MICROTUBE LENGTHS BY KNOWING THE  *
C    * HEAD PRESSURE DISTRIBUTION ALONG THE LATERAL .                   *
C    ******************************************************************
      SUBROUTINE SPLTH(Q,DS,N,G,VK,HBL)
      DIMENSION BL(200),H(200)
      V=(4*Q)/(3.14156*(DS**2))
      CALL FRIC (Q,VK,DS,F)
      BJ=(F*(V**2))/(2*G*DS)
      DO 200 I=1,N
      BL(I)=H(I)/BJ
  200 CONTINUE
      RETURN
      END
```

Figure (A.2.b) Subroutine for Microtube Length Without Coils Determination

Q - *microtube discharge*

VK - *kinematic viscosity*

DS - *microtube diameter*

H(I) - *total head at the microtube (I)*

G - *specific gravity*

N - *number of microtubes*

V - *folw velocity*

BJ - *friction head loss per unit length*

BL(I) - *microtube (I) length*

NL(I) - *number of coils*

NN,NR - *dummy variables*

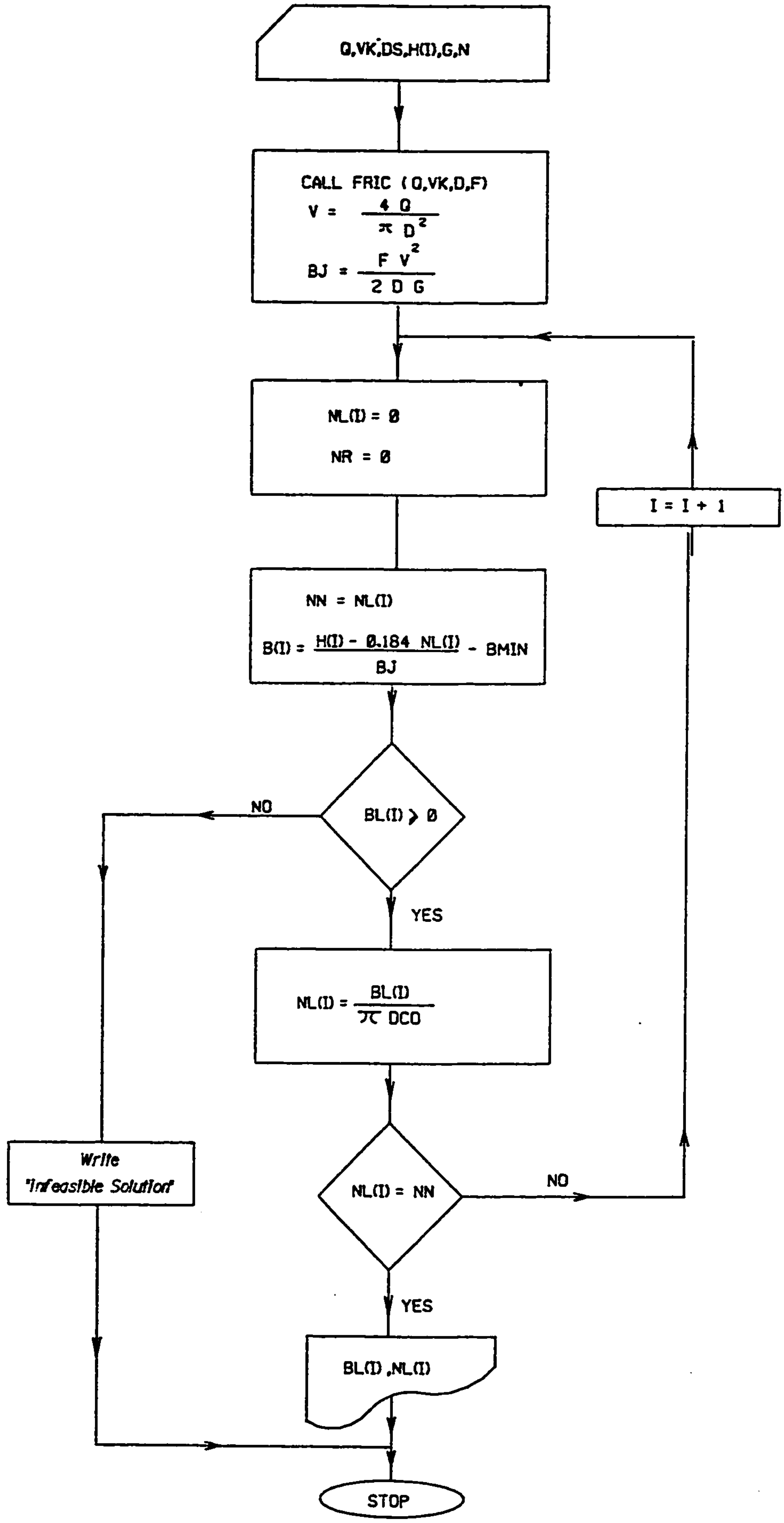


Figure (A3.a) Flow Chart for Microtube Length With Coils

```
C    ******************************************************************
C    * THIS SUBROUTINE CALCULATES THE MICROTUBE LENGTHS BY KNOWING THE  *
C    * HEAD PRESSURE DISTRIBUTION ALONG THE LATERAL .                   *
C    ******************************************************************
      SUBROUTINE SPLTH(IER,Q,DS,N,G,VK,H,DCO,BMIN,NL,BL,TT,NAN)
      DIMENSION BL(200),H(200),NL(200)
      V=(4*Q)/(3.14156*(DS**2))
      CALL FRIC (Q,VK,DS,F)
      BJ=(F*(V**2))/(2*G*DS)
      DO 200 I=1,N
      NR=0
      NL(I)=0
  160 NN=NL(I)
      BL(I)=((H(I)-(0.184*NN))/(BJ))-BMIN
      TT=BL(I)
      IF(TT.GE.-0.000001)GO TO 180
      IF(IER.EQ.3)GO TO 170
      CALL COND1 (NAN)
      GO TO 210
  170 CALL COND3 (NAN)
      GO TO 210
  180 NL(I)=(BL(I))/(3.14159*DCO)
      NAN=0
      IF(NL(I).EQ.NR)GO TO 190
      NR=NN
      BL(I)=BL(I)+BMIN
      NON=NL(I)-NN
      IF(NON.GT.0.1)GO TO 160
      GO TO 200
  190 BL(I)=(H(I)-(0.184*NL(I)))/(BJ)
  200 CONTINUE
  210 RETURN
      END
```

Figure (A.3.b) Subroutine for Microtube Length with Coils Determination

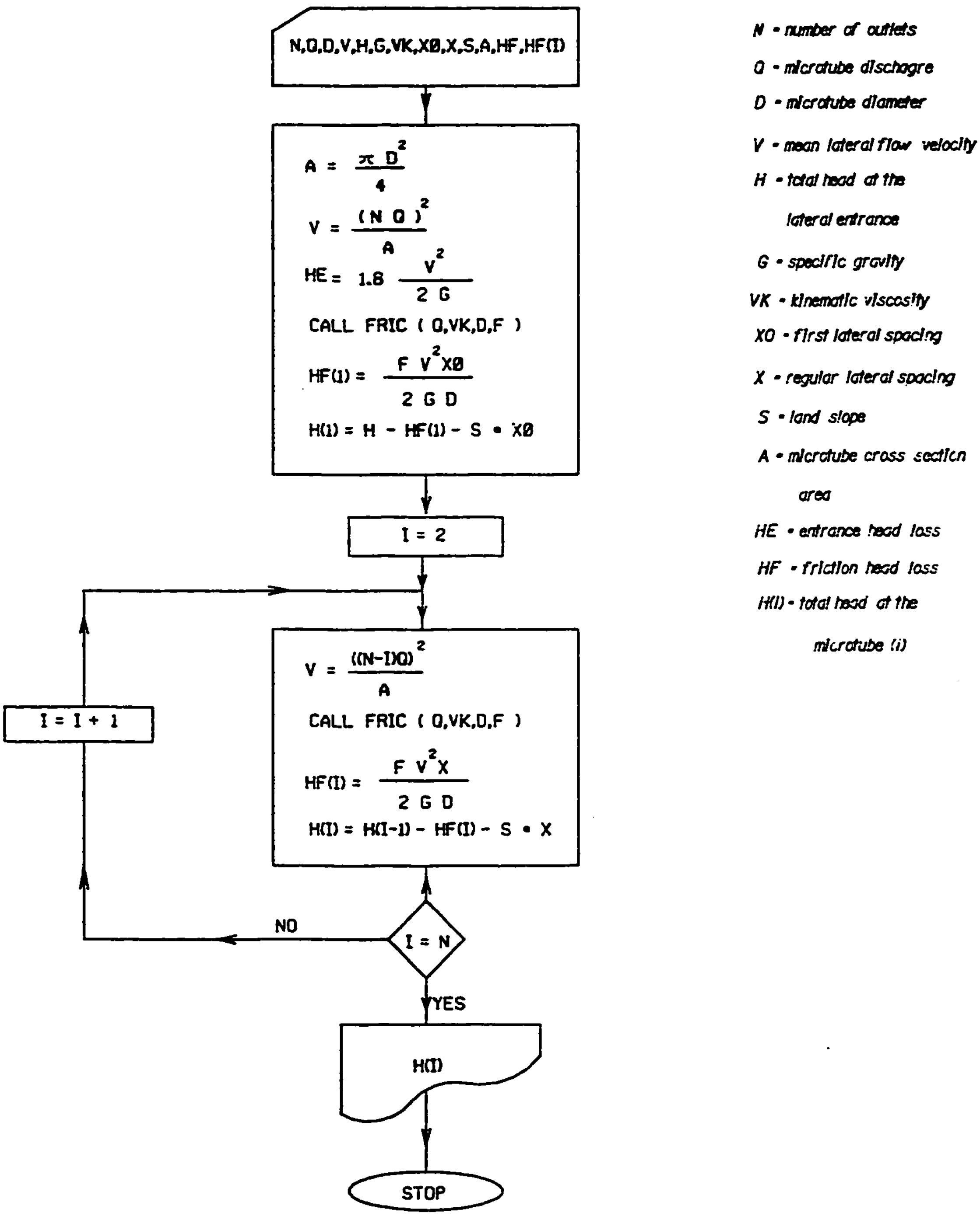
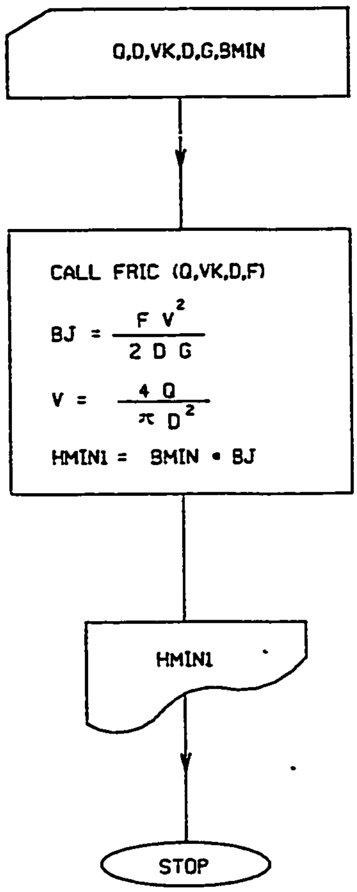


Figure (A.4.a) Flow Chart for the total Head Distribution Along the Lateral

```
C     ********************************************************************
C     *   THIS SUBROUTINE CALCULATES THE PRESSURE HEAD DISTRIBUTION      *
C     *   ALONG THE LATERAL                                              *
C     ********************************************************************
      SUBROUTINE HEDIS (Q,D,HO,H,N,S,XO,X,VK,G)
      DIMENSION H(200),HF(200),S(200)
      A=3.141*(D**2)/4
      V=(N*Q)/A
      QI=(N*Q)
      CALL FRIC(QI,VK,D,F)
      HE=(1.8*(V**2))/(2*G)
      HF(1)=F*XO*(V**2)/(2*G*D)
      H(1)=HO-HF(1)-HE+S(1)*XO
      IF(N.LT.2)GO TO 130
      NM=N-1
      DO 120 I=1,NM
      J=I+1
      IL=NM-I+1
      V=(IL*Q)/A
      QI=(IL*Q)
      CALL FRIC(QI,VK,D,F)
      HF(J)=F*X*(V**2)/(2*G*D)
      H(J)=H(I)-HF(J)+S(J)*X
  120 CONTINUE
  130 RETURN
      END
```

Figure (A.4.b) Subroutine for the Total Head Distribution Along the Lateral Determination



Q - microtube discharge

D - microtube diameter

V - mean lateral flow velocity

VK - kimeamatic viscosity

G - specific gravity

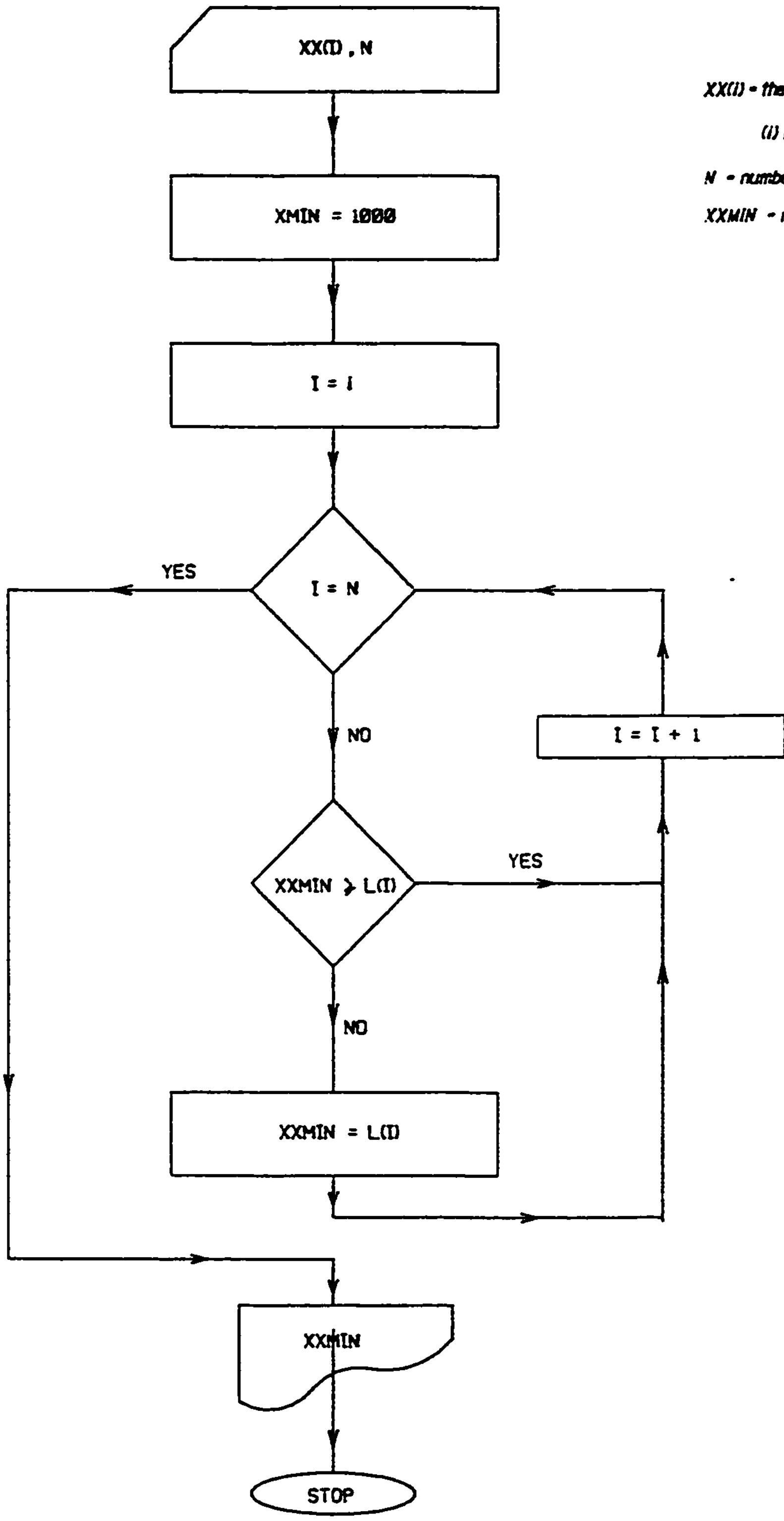
BMIN - practical minimum microtube length

HMIN1 - minimum required total head

Figure (A5.a) Flow Chart for Minimum Required Total Head

```
C    *****************************************************************
C    * THIS SUBROUTINE CALCULATES MINIMUM MICROTUBE HEAD NEEDED FOR THE *
C    * REQUIRED MICROTUBE LENGTH .                                      *
C    *****************************************************************
      SUBROUTINE MIN1(Q,VK,DS,G,BMIN,HMIN1)
      CALL FRIC (Q,VK,DS,F)
      V=(4*Q)/(3.14156*(DS**2))
      BJ=(F*(V**2))/(2*G*DS)
      HMIN1=(BMIN)*BJ
      RETURN
      END
```

Figure (A.5.b) Subroutine for Minimum Required Total Head Determination



XX(I) = the value of the variable (i) in XX set of variable

N = number of variables

XXMIN = minimum value of the set XX variables

Figure (A6.a) Flow Chart for Minimum Value of a Set of Values

```
C     *******************************************************************
C     * THIS SUBRIOUTINE DETERMINES THE MINIMUM VALUE OF A SET VALUES   *
C     *******************************************************************
      SUBROUTINE XXMIN(XX,N,XMIN)
      DIMENSION XX(200)
      XMIN=100
      DO 110 I=1,N
       IF (XMIN.LT.XX(I))GO TO 110
        XMIN=XX(I)
  110 CONTINUE
      RETURN
      END
```

Figure (A.6.b) Subroutine for Minimum Value of a Set of Values Determination

XX(I) - the value of the variable (I) in XX set of variable

N - number of variables

XXMAX - maximum value of the set XX variables

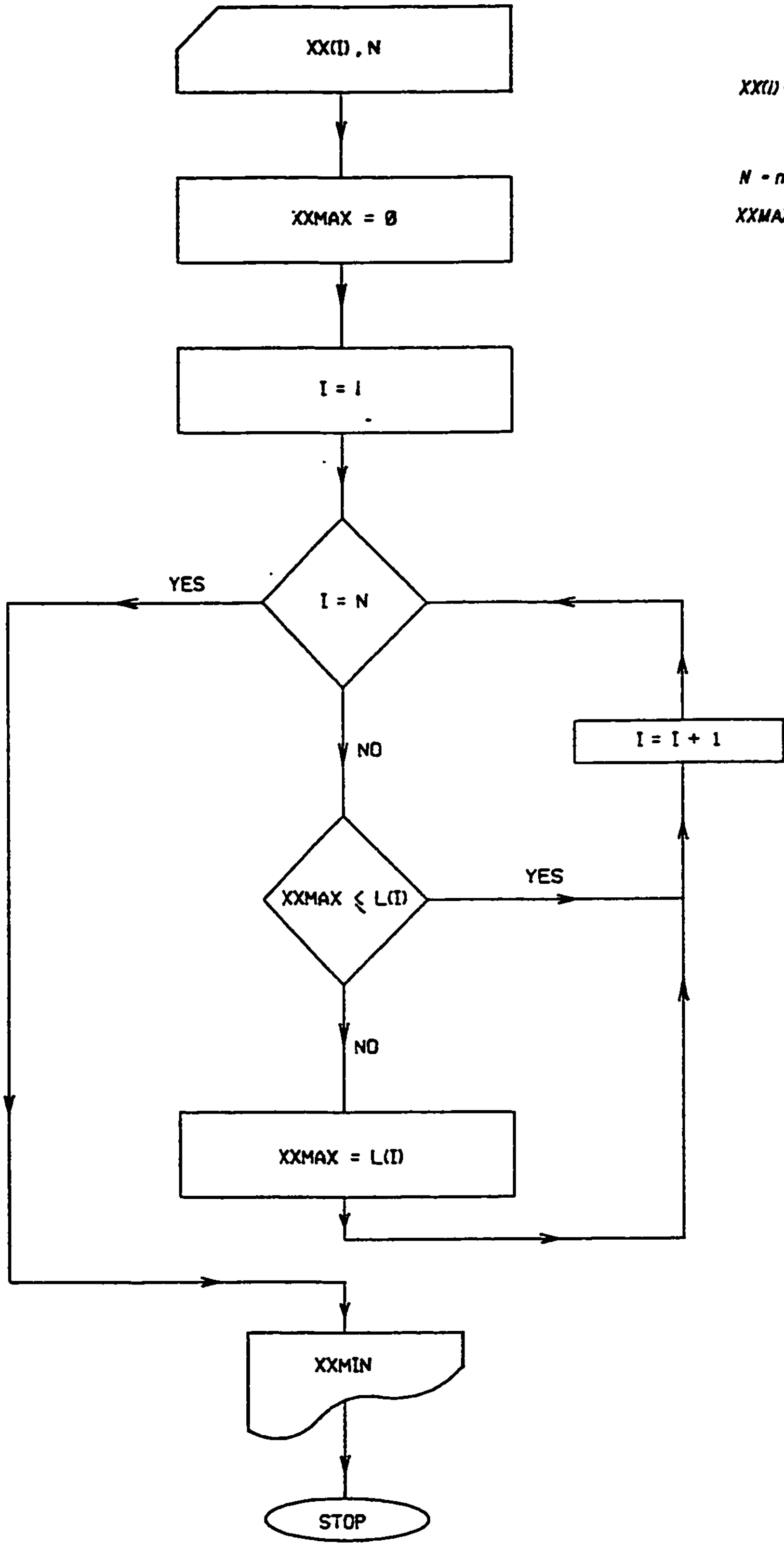
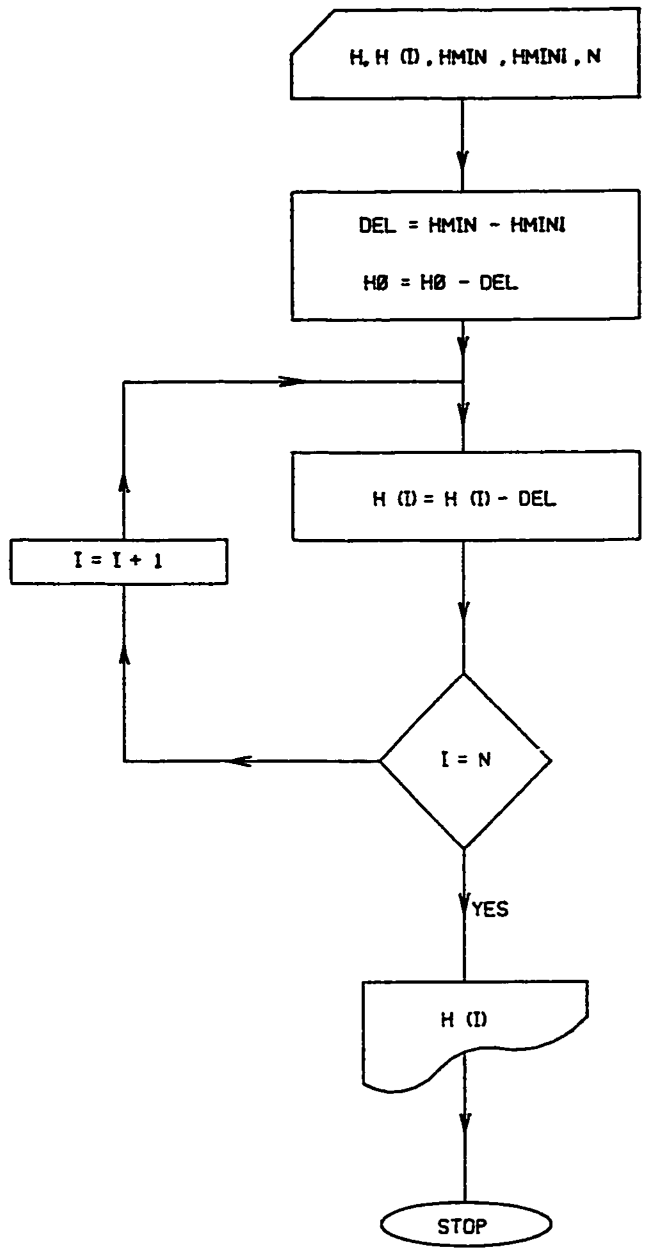


Figure (A.7.a) Flow Chart of Maximum Value of a Set of Values

```
C    **********************************************************************
C    * THIS SUBRIOUTINE DETERMINES THE MAXIMUM VALUE OF A SET VALUES     *
C    **********************************************************************
      SUBROUTINE XXMAX(XX,N,XMAX)
      DIMENSION XX(200)
      XMAX=0
      DO 100 I=1,N
       IF (XMAX.GT.XX(I))GO TO 100
        XMAX=XX(I)
  100 CONTINUE
      RETURN
      END
```

Figure (A.7.b) Subroutine for Maximum Value of a Set of Values Determination



H0 - total head at the lateral entrance

H(I) - total head st the microtube (I)

HMINI - minimum required total head

HMIN - minimum calculated total head

N - number of microtubes

DEL - difference between the required and calculated total heads

Figure (A.8.a) Flow Chart for Adjusting the Total Head Distribution Along the Lateral

```
C     ***********************************************************************
C     * THIS SUBROUTINE ADJUSTS THE HEAD PRESSURE DISTRIBUTION ALONG THE *
C     * LATERAL                                                           *
C     ***********************************************************************
      SUBROUTINE ADJ(HMIN1,HMIN,HO,N,H)
      DIMENSION H(200)
      DEL=HMIN-HMIN1
      HO=HO-DEL
      DO 220 I=1,N
      H(I)=H(I)-DEL
  220 CONTINUE
      RETURN
      END
```

Figure (A.8.b) Subroutine for Adjusting The Total Head Distribution Along the Lateral

Figure (A.9) The Computer Program for Lateral Design


```
$JOB
CPRINTOFF
C***********************************************************************
C
C    MICROTUBES AND LATERAL IN DRIP IRRIGATION NETWORK SYSTEM DESIGN
C
C     ******************************************************
C     *                                                    *
C     *    DEVELOPED BY:                                   *
C     *                                                    *
C     *        MUHAMMED ABDEL-RAHMAN IBRAHIM               *
C     *        STUDENT # 849734, DEPT. OF CIVIL ENGG.      *
C     *        KING FAHD UNIVERSITY OF PETROLEUM & MINERALS *
C     *        DHAHRAN, SAUDI ARABIA                       *
C     *                                                    *
C     ******************************************************
C
C    *********
C    NOTATIONS
C    *********
C    NOTATIONS
C    *********
C    H(I)   =  PRESSURE AT THE MICROTUBE ENTRANCE
C    HF(I)  =  FRICTION HEAD LOSS AT THE PIPE SECTION (I)
C    BL(I)  =  THE MICROTUBE LENGTH
C    S(I)   =  THE LAND SLPOE AT SECTION (I)
C    XX(I)  =  DUMMAY ARRAY
C    NN     =  DUMMAY VARIABLE
C    NL(I)  =  NUMBER OF COILS IN EACH MICROTUBE
C    NOL    =  NUMBER OF LATERALS TO BE DESIGNED
C    IER    =  CONTROL VARIABLE TO GUIDE THE DESIGN CASE , WHICH EQUALS
C           =     A VALUE OF 1 IN CASE I,
C           =     2 A VALUE OF IN CASE II,
C           =     AND 3 A VALUE OF IN CASE III
C    IEA    =  CONTROL VARIABLE TO GUIDE THE SOLPE
C           =  0 WHEN THE SLOPE IS UNIFORM
C           =  1 WHEN THE SLOPE CHANGES FROM SECTION TO SECTION
C    N      =  NO. OF MICROTUBES
C    XO     =  THE DISTANCE BETWEEN THE FIRST MICROTUBE AND THE LATERAL
C              ENTRANCE
C    X      =  SPACING BETWEEN MICROTUBES
C    DS     =  MICROTUBE DIAMETER, METER
C    BMIN   =  REQUIRED MINIMUM MICROTUBE LENGTH, METER
C    DCO   =  DIA. OF COIL, METER
C    G      =  ACCELERATION DUE TO GRAVITY = 9.81 M/SQ. SEC
C    VK     =  THE KINEMATIC VISCOSITY
C    SLOPE  =  THE LAND SLPOE WHEN THE SLOPE IS UNIFORM
C    Q      =  DISCHARGE AT EACH MICROTUBE
C    HO     =  THE PRESSURE HEAD AT THE LATERAL ENTRANCE
C    D      =  LATERAL DIAMETER, METER
C    QS     =  DISCHARGE AT DIFFERENT BRANCH POINTS
C    QS     =  TOTAL LATERAL DISCHARGE
C    TLEN   =  TOTAL LATERAL LENGTH
C    TT     =  DUMMAY VARIABLE
C    NAN    =  DUMMAY VARIABLE
```

Cont. Figure (A.9) The Computer Program for Lateral Design

```
C     BMIN    =  MINIMUM CALCULATED MICROTUBE LENGTH
C     BMAX    =  MAXIMUM CALCULATED MICROTUBE LENGTH
C     HMIN    =  MINIMUM CALCULATED TOTAL HEAD
C     HMAX    =  MAXIMUM CALCULATED TOTAL HEAD
C     HMIN1   =  MINIMUM REQUIRED MICROTUBE LENGTH
C     QTEST   =  DUMMAY VARIABLE
C     A       =  MICROTUBE CROSS SECTION AREA
C     V       =  VELOCITY OF FLOW
C     QI      =  LATERAL DISCHARGE AT DIFFERENT PIPE SECTIONS
C     NR      =  DUMMAY VARIABLE
C     NON     =  DUMMAY VARIABLE
C     DEL     =  DIFFERANCE BETWEEN THREQUIRED AND CALCULATED
C                MICROTUBE LENGTH
C
C**********************************************************************
C
C     DEFINITION SKETCH:
C
C
C     |   |
C     |   |<------SUBMAIN PIPE        _ _ LATERAL
C     |   |                          /     PIPE DIA. = D
C     |   |                         /     (DIA. D1)
C     |   |--XO---|                /          ||              |-- X--|
C     |   |_______________________/___________..______________________
C     |    _______ ______ ______ ______ ______||______ _______ ______ _|
C     |   |0      |1     |2     |3     |4      ..     |(N-2) |(N-1)  |N
C     |   |       |      |      |      |       ||     |      |       |
C     |   |       |      |      |      |       ..     |      |       |
C                 |      |      |      |       ||     |      |      /V
C                 |      |      |      |       ..     |\     V    /  Q
C                 |      |      |      |       ||     V  \   Q  /
C                 |      |      |      |       ..     Q    \  /
C                 |      |      |      V       ||       MICROTUBE
C                 |      |      V      Q                PIPE DIA. = DS
C                 |      V      Q
C                 V      Q
C                 Q
C
C
C**********************************************************************
      DIMENSION H(200),HF(200),BL(200),S(200),XX(200)
      INTEGER NN,NL(200)
      READ(5,*)NOL
      DO 555 J=1,NOL
      READ(5,*)IER,IEA
      READ(5,*)N,XO,X,DS,BMIN,DCO
      CALL WRITE (J)
      G  = 9.81
      VK = 0.000001
C
C     ****************************************************************
C     *     IF THERE IS A UNIFORM SLOPE   IEA = 0                     *
C     ****************************************************************
      IF(IEA.EQ.0)GO TO 10
```

```
C     ************************************************************************
C     *    IF THERE IS MORE THAN ONE SLOPE IEA = 1                           *
C     ************************************************************************
      IF(IEA.EQ.1)GO TO 30
C
   10 READ(5,*)SLOPE
      DO 20 I=1,N
      S(I)=SLOPE
   20 CONTINUE
      GO TO 40
C
   30 READ(5,*)(S(I),I=1,N)
C     ************************************************************************
C     *   CASE I " KNOWN Q & HO "    IER = 1                                  *
C     ************************************************************************
   40 IF(IER.EQ.1)GO TO 50
C     ************************************************************************
C     *   CASE II " KNOWN Q & D "    IER = 2                                  *
C     ************************************************************************
      IF(IER.EQ.2)GO TO 60
C     ************************************************************************
C     *   CASE III " KNOWN D & HO " IER = 3                                   *
C     ************************************************************************
      IF(IER.EQ.3)GO TO 70
C
C     ****************************************************         ********
C     *                                                  *
C     *               CASE I   " KNOWN Q & HO "          *
C     *                                                  *
C     ****************************************************         ********
C
   50 READ(5,*)Q,HO
      READ(5,*)D
      CALL WRITE1(Q,QN,TLEN,HO,D,DS,X,XO,N,DCO,BMIN)
      CALL CONVER(Q,D,DS,BMIN,DCO)
      CALL HEDIS (Q,D,HO,H,N,S,XO,X,VK,G)                           LAS00060
      CALL SPLTH(IER,Q,DS,N,G,VK,H,DCO,BMIN,NL,BL,TT,NAN)
      IF(NAN.EQ.1)GO TO 555
      CALL XXMIN(H,N,HMIN)                                          LAS00070
      CALL XXMAX(H,N,HMAX)                                          LAS00080
      CALL XXMIN(BL,N,BMIN)                                         LAS00070
      CALL XXMAX(BL,N,BMAX)                                         LAS00080
      CALL WRITE2(N,H,NL,BL,S,HMAX,HMIN,BMAX,BMIN)
      GO TO 555
C
C     ****************************************************         ********
C     *                                                  *
C     *               CASE II " KNOWN Q & D "            *
C     *                                                  *
C     ****************************************************         ********
C
   60 READ(5,*)Q,D
      HO=100
      CALL WRITE3(Q,QN,TLEN,HO,D,BMIN,DS,X,XO,N,DCO)
      CALL CONVER(Q,D,DS,BMIN,DCO)
```

Cont. Figure (A.9) The Computer Program for Lateral Design

```
      CALL HEDIS (Q,D,HO,H,N,S,XO,X,VK,G)                              LAS00060
      CALL MIN1(Q,VK,DS,G,BMIN,HMIN1)                                  LAS00740
      CALL XXMIN(H,N,HMIN)                                             LAS00070
      CALL ADJ(HMIN1,HMIN,HO,N,H)                                      ADJ00020
      CALL SPLTH(IER,Q,DS,N,G,VK,H,DCO,BMIN,NL,BL,TT,NAN)              N00030
      IF(NAN.EQ.1)GO TO 555
      CALL WRITE4(N,H,NL,BL,S,HO)
      GO TO 555
C
C     ***************************************************              ********
C     *                                                 *
C     *              CASE III " KNOWN H & D "           *
C     *                                                 *
C     ***************************************************              ********
C
   70 READ(5,*)HO,D
      Q=100
      HH=HO
      CALL WRITE5(TLEN,HO,D,DS,X,XO,N,DCO,BMIN)
      CALL CONVER(Q,D,DS,BMIN,DCO)
   80 CALL HEDIS (Q,D,HH,H,N,S,XO,X,VK,G)                              LAS00060
      CALL MIN1(Q,VK,DS,G,BMIN,HMIN1)                                  LAS00740
      CALL XXMIN(H,N,HMIN)                                             LAS00070
      CALL ADJ(HMIN1,HMIN,HH,N,H)                                      ADJ00020
      IF(ABS(HH-HO).LT.0.001)GO TO 90
      Q=Q*((HO/HH)**0.5714)
      QTEST=Q*1000*3600
      IF (QTEST.GT.0.01)GO TO 80
      CALL COND3 (NAN)
      GO TO 555
   90 CALL SPLTH(IER,Q,DS,N,G,VK,H,DCO,BMIN,NL,BL,TT,NAN)
      IF(NAN.EQ.1)GO TO 555
      CALL WRITE6(Q,N,H,NL,BL,S)
C
  555 CONTINUE
  999 STOP                                                             LAS00150
      END                                                              LAS00160
C     ********************************************************************
C     * THIS SUBRIOUTINE DETERMINES THE MAXIMUM VALUE OF A SET VALUES   *LAS00170
C     ********************************************************************
      SUBROUTINE XXMAX(XX,N,XMAX)                                      LAS00180
      DIMENSION XX(200)                                                LAS00190
      XMAX=0                                                           LAS00200
      DO 100 I=1,N                                                     LAS00210
       IF (XMAX.GT.XX(I))GO TO 100                                     LAS00220
        XMAX=XX(I)                                                     LAS00230
  100 CONTINUE                                                         LAS00240
      RETURN                                                           LAS00250
      END                                                              LAS00260
C     ********************************************************************
C     * THIS SUBRIOUTINE DETERMINES THE MINIMUM VALUE OF A SET VALUES   *LAS00170
C     ********************************************************************
      SUBROUTINE XXMIN(XX,N,XMIN)                                      LAS00280
      DIMENSION XX(200)                                                LAS00290
      XMIN=100                                                         LAS00300
```

Cont. Figure (A.9) The Computer Program for Lateral Design

```
      DO 110 I=1,N                                                      LAS00310
       IF (XMIN.LT.XX(I))GO TO 110                                      LAS00320
        XMIN=XX(I)                                                      LAS00330
  110 CONTINUE                                                          LAS00340
      RETURN                                                            LAS00350
      END                                                               LAS00360
C    *******************************************************************
C    *   THIS SUBROUTINE CALCULATES THE PRESSURE HEAD DISTRIBUTION      *
C    *   ALONG THE LATERAL                                              *
C    *******************************************************************
      SUBROUTINE HEDIS (Q,D,HO,H,N,S,XO,X,VK,G)                         LAS00400
      DIMENSION H(200),HF(200),S(200)                                   LAS00410
      A=3.141*(D**2)/4                                                  LAS00420
      V=(N*Q)/A                                                         LAS00430
      QI=(N*Q)                                                          LAS00440
      CALL FRIC(QI,VK,D,F)                                              LAS00450
      HE=(1.8*(V**2))/(2*G)
      HF(1)=F*XO*(V**2)/(2*G*D)                                         LAS00460
      H(1)=HO-HF(1)-HE+S(1)*XO                                          LAS00470
      IF(N.LT.2)GO TO 130
      NM=N-1
      DO 120 I=1,NM                                                     LAS00480
      J=I+1                                                             LAS00490
      IL=NM-I+1
      V=(IL*Q)/A                                                        LAS00510
      QI=(IL*Q)                                                         LAS00520
      CALL FRIC(QI,VK,D,F)                                              LAS00530
      HF(J)=F*X*(V**2)/(2*G*D)                                          LAS00540
      H(J)=H(I)-HF(J)+S(J)*X                                            LAS00550
  120 CONTINUE                                                          LAS00560
  130 RETURN                                                            LAS00570
      END                                                               LAS00580
C    *********************************************************************
C    * THIS SUBROUTINE CALCULATES THE FRICTION COEFICENT FOR A PIPE.    *LAS00590
C    *********************************************************************
      SUBROUTINE FRIC(Q,VK,D,F)                                         LAS00600
      V=(4*Q)/(3.14159*(D**2))                                          LAS00610
      RN=(V*D)/VK                                                       LAS00620
      IF(RN.GT.2100)GO TO 140                                           LAS00630
        F=64/RN                                                         LAS00640
         GO TO 150                                                      LAS00650
  140   F=0.316/(RN**0.25)                                              LAS00670
  150 RETURN                                                            LAS00700
      END                                                               LAS00710
C    *********************************************************************
C    * THIS SUBROUTINE CALCULATES MINIMUM MICROTUBE HEAD NEEDED FOR THE *LAS00590
C    * REQUIRED MICROTUBE LENGTH .                                       *
C    *********************************************************************
      SUBROUTINE MIN1(Q,VK,DS,G,BMIN,HMIN1)                             LAS00740
      CALL FRIC (Q,VK,DS,F)                                             LAS00750
      V=(4*Q)/(3.14156*(DS**2))                                         LAS00760
      BJ=(F*(V**2))/(2*G*DS)                                            LAS00770
      HMIN1=(BMIN)*BJ                                                   LAS00780
      RETURN                                                            LAS00810
      END                                                               LAS00820
```

Cont. Figure (A.9) The Computer Program for Lateral Design


```
C    ************************************************************************
C    * THIS SUBROUTINE CALCULATES THE MICROTUBE.LENGTHS BY KNOWING THE  *LAS00590
C    * HEAD PRESSURE DISTRIBUTION ALONG THE LATERAL .                  *
C    ************************************************************************
      SUBROUTINE SPLTH(IER,Q,DS,N,G,VK,H,DCO,BMIN,NL,BL,TT,NAN)
      DIMENSION BL(200),H(200),NL(200)
      V=(4*Q)/(3.14156*(DS**2))                                        MIN00110
      CALL FRIC (Q,VK,DS,F)                                            MIN00090
      BJ=(F*(V**2))/(2*G*DS)                                           MIN00120
      DO 200 I=1,N
      NR=0
      NL(I)=0
  160 NN=NL(I)
      BL(I)=((H(I)-(0.184*NN))/(BJ))-BMIN
      TT=BL(I)
      IF(TT.GE.-0.000001)GO TO 180
      IF(IER.EQ.3)GO TO 170
      CALL COND1 (NAN)
      GO TO 210
  170 CALL COND3 (NAN)
      GO TO 210
  180 NL(I)=(BL(I))/(3.14159*DCO)
      NAN=0
      IF(NL(I).EQ.NR)GO TO 190
      NR=NN
      BL(I)=BL(I)+BMIN
      NON=NL(I)-NN
      IF(NON.GT.0.1)GO TO 160
      GO TO 200
  190 BL(I)=(H(I)-(0.184*NL(I)))/(BJ)
  200 CONTINUE
  210 RETURN                                                           MIN00160
      END                                                              MIN00170
C    ************************************************************************
C    * THIS SUBROUTINE ADJUSTS THE HEAD PRESSURE DISTRIBUTION ALONG THE *
C    * LATERAL                                                          *
C    ************************************************************************
      SUBROUTINE ADJ(HMIN1,HMIN,HO,N,H)                                ADJ00020
      DIMENSION H(200)                                                 ADJ00030
      DEL=HMIN-HMIN1                                                   ADJ00040
      HO=HO-DEL                                                        ADJ00050
      DO 220 I=1,N                                                     ADJ00060
      H(I)=H(I)-DEL                                                    ADJ00070
  220 CONTINUE                                                         ADJ00080
      RETURN                                                           ADJ00090
      END                                                              ADJ00100
C    ************************************************************************
C    * THIS SUBROUTINE CONVERTES THE DISCHARGE FROM L/H TO M3/S         *
C    * AND THE DIAMETER FROM MM TO M                                    *
C    ************************************************************************
      SUBROUTINE CONVER(Q,D,DS,BMIN,DCO)                               ADJ00020
      Q=(Q/1000)/3600
      D=D/1000
      DS=DS/1000
      BMIN=BMIN/100
```

```
      DCO=DCO/100
      RETURN                                                            ADJ00090
      END                                                               ADJ00100
C     ******************************************************************
C     * THIS SUBROUTINE WRITES THE OUT PUT IN A SUITABLE FORMAT .      *
C     ******************************************************************
      SUBROUTINE WRITE1(Q,QN,TLEN,HO,D,DS,X,XO,N,DCO,BMIN)
      NNN=N-1
      TLEN=XO+(NNN*X)
      QN=N*Q
      WRITE(6,230)Q,HO,DS,N,QN,TLEN,DCO,BMIN
 230  FORMAT(/15X,
     *' DISCHARGE AT EACH MICROTUBE     = ',F10.4,'  L/H    ',/15X,
     *' THE HEAD AT THE ENTRANCE        = ',F10.4,'  METER  ',/15X,
     *' THE MICROTUBE DIAMETER          = ',F10.4,'  MM     ',/15X,
     *' NUMBER OF MICROTUBES            =   ',I3,'  MICROTUBES',/15X,
     *' TOTAL DISCHARGE                 = ',F10.4,'  L/H    ',/15X,
     *' TOTAL LATERAL PIPE LENGTHS      = ',F10.4,'  METER  ',/15X,
     *' THE COIL DIAMETER               = ',F10.4,'  CM     ',/15X,
     *' REQUIRED MIN. MICROTUBE LENGTH = ',F10.4,'  CM     ',/)
      WRITE(6,240)D
 240  FORMAT(/,8X,
     *'**************** THE ASSUMED LATERAL DIAMETER ='
     *,F10.4,' MM ***************',/)
      RETURN
      END
C     ******************************************************************
C     * THIS SUBROUTINE WRITES THE OUT PUT IN A SUITABLE FORMAT .      *
C     ******************************************************************
      SUBROUTINE WRITE2(N,H,NL,BL,S,HMAX,HMIN,BMAX,BMIN)
      DIMENSION H(200),BL(200),NL(200),S(200)
      WRITE(6,250)
 250  FORMAT(20X,'LAND SLOPE / TOTAL HEAD / NUMBER OF COILS / MIC.  LENG
     *TH'
     */,23X,'(M/M)',8X,'(M)',30X,'(CM)')
      DO 270  I = 1,N
      BL(I)=BL(I)*100
      WRITE(6,260) I,S(I),H(I),NL(I),BL(I)
 260  FORMAT(4X,
     *'MICROTUBE #',I3,': ',F8.4,5X,F8.4,12X,I2,11X,F9.5)
 270  CONTINUE
      WRITE(6,280)HMAX,HMIN,BMAX,BMIN                                   LAS00100
 280  FORMAT(//,5X,'THE MAXIMUM PRESSURE HEAD = ',F8.4,' M'
     */,5X,'THE MINIMUM PRESSURE HEAD = ',F8.4,' M'
     * //,5X,'THE MAXIMUM MICROTUBE LENGTH  = ',F8.4,' M',
     */,5X,'THE MINIMUM MICROTUBE LENGTH  = ',F8.4,' M',///)
      RETURN
      END
C     ******************************************************************
C     * THIS SUBROUTINE WRITES THE OUT PUT IN A SUITABLE FORMAT .      *
C     ******************************************************************
      SUBROUTINE WRITE3(Q,QN,TLEN,HO,D,BMIN,DS,X,XO,N,DCO)
      TLEN=XO+(N*X)
      QN=N*Q
      WRITE(6,290) Q,D,DS,N,QN,TLEN,DCO,BMIN
```

Cont. Figure (A.9) The Computer Program for Lateral Design


```
 290  FORMAT(/15X,
     *' DISCHARGE AT EACH MICROTUBE     =',F10.4,' L/H  ',/15X,
     *' THE LATERAL DIAMETER            =',F10.4,' MM   ',/15X,
     *' THE MICROTUBE DIAMETER          =',F10.4,' MM   ',/15X,
     *' THE NUMBER OF MICROTUBES        =  ',I3 ,'  MICROEUBES',/15X,
     *' TOTAL DISCHARGE                 =',F10.4,' L/H  ',/15X,
     *' TOTAL LATERAL PIPE LENGTHS      =',F10.4,' METER',/15X,
     *' THE COIL DIAMETER               =',F10.4,' CM   ',/15X,
     *' REQUIRED MIN. MICROTUBE LENGTH =',F10.4,' CM   ',/15X,/)
      RETURN
      END
C    ********************************************************************
C    * THIS SUBROUTINE WRITES THE OUT PUT IN A SUITABLE FORMAT .        *
C    ********************************************************************
      SUBROUTINE WRITE4(N,H,NL,BL,S,HO)
      DIMENSION H(200),BL(200),NL(200),S(200)
      WRITE(6,300)
 300  FORMAT(20X,'LAND SLOPE / TOTAL HEAD / NUMBER OF COILS / MIC.  LENG
     *TH'
     */,23X,'(M/M)',9X,'(M)',28X,'(CM)')
      DO 320  I = 1,N
      BL(I)=BL(I)*100
      WRITE(6,310) I,S(I),H(I),NL(I),BL(I)
 310  FORMAT(4X,
     *'MICROTUBE #',I3,': ',F8.4,5X,F8.4,12X,I2,11X,F9.5)
 320  CONTINUE
      WRITE(6,330)HO                                                  LAS00100
 330  FORMAT(//,5X,'THE REQUIRED TOTAL HEAD AT THE LATERAL ENTRANCE  '
     *,'= ',F8.4,
     *' METER',///)
      RETURN
      END
C    ********************************************************************
C    * THIS SUBROUTINE WRITES THE OUT PUT IN A SUITABLE FORMAT .        *
C    ********************************************************************
      SUBROUTINE WRITE5(TLEN,HO,D,DS,X,XO,N,DCO,BMIN)
      TLEN=XO+(N*X)
      WRITE(6,340) HO,D,DS,TLEN,DCO,BMIN
 340  FORMAT(/15X,
     *' THE HEAD AT THE ENTRERENCE  =',F10.4,'  METER',/15X,
     *' THE LATERAL DIAMETER        =',F10.4,'  MM   ',/15X,
     *' THE MICROTUBE DIAMETER      =',F10.4,'  MM   ',/15X,
     *' TOTAL LATERAL PIPE LENGTHS  =',F10.4,'  METER',/15X,
     *' THE COIL DIAMETER           =',F10.4,'  CM   ',/15X,
     *' REQUIRED MIN. MICROTUBE LENGTH =',F10.4,' CM   ',/15X,/)
      RETURN
      END
C    ********************************************************************
C    * THIS SUBROUTINE WRITES THE OUT PUT IN A SUITABLE FORMAT .        *
C    ********************************************************************
      SUBROUTINE WRITE6(Q,N,H,NL,BL,S)
      DIMENSION H(200),BL(200),NL(200),S(200)
      WRITE(6,350)
 350  FORMAT(20X,'LAND SLOPE / TOTAL HEAD / NUMBER OF COILS / MIC.  LENG
     *TH'
```

Cont. Figure (A.9) The Computer Program for Lateral Design


```
     */,23X,'(M/M)',9X,'(M)',28X,'(CM)')
      DO 370  I = 1,N
      BL(I)=BL(I)*100
      WRITE(6,360) I,S(I),H(I),NL(I),BL(I)
 360  FORMAT(4X,
     *'MICROTUBE #',I3,': ',F8.4,5X,F8.4,12X,.2,11X,F9.5)
 370  CONTINUE
      Q=Q*1000*3600
      WRITE(6,380)Q
 380  FORMAT(//,5X,' DISCHARGE AT EACH MICROTUBE  =',F10.4,' L/H'///)
      RETURN
      END
C
      SUBROUTINE COND1 (NAN)
      NAN=1
      WRITE(6,390)
 390  FORMAT(15X,' ENFEASIBLE SOLUTION , EITHER ',//,
     *15X,' INCREASE THE LATERAL DIAMETER; ',/,
     *15X,' INCREASE THE MICROTUBE DIAMETER; ',/,
     *15X,' OR DECREASE THE MIN. MICROTUBRE LENGTH '/// )
      RETURN
      END
C
      SUBROUTINE COND3 (NAN)
      NAN=1
      WRITE(6,400)
 400  FORMAT(15X,' ENFEASIBLE SOLUTION , EITHER ',//,
     *15X,' INCREASE THE MICROTUBE DIAMETER; ',/,
     *15X,' OR DECREASE THE MIN. MICROTUBRE LENGTH '/// )
      RETURN
      END
C
      SUBROUTINE WRITE (J)
      IF(J.GT.1)GO TO 420
      WRITE(6,410)
 410  FORMAT(//,8X,' **************************************************
     ***********',/,6X,'*************   THE CLCULATIONS OF THE LATERAL'
     *,' # 1  **************',/,9X,
     *'**********************************************************')
      GO TO 440
 420  WRITE(6,430) J
 430  FORMAT(/////,8X,' **************************************************
     ************',/,6X,'************   THE CLCULATIONS OF THE '
     *,' LATERAL #',I2,'  *************',/,9X,
     *'**********************************************************')
 440  CONTINUE
      RETURN
      END
C*********************************************************************
C       THE END OF THE PROGRAM                                ********
C*********************************************************************
$ENTRY
```

```
   ************************************************************
*************    THE CLCULATIONS OF THE LATERAL # 1   ***************
   ************************************************************

         DISCHARGE AT EACH MICROTUBE      =     20.0000  L/H
         THE HEAD AT THE ENTRANCE         =      7.0000  METER
         THE MICROTUBE DIAMETER           =      1.5000  MM
         NUMBER OF MICROTUBES             =     10   MICROTUBES
         TOTAL DISCHARGE                  =    200.0000  L/H
         TOTAL LATERAL PIPE LENGTHS       =     95.0000  METER
         THE COIL DIAMETER                =     10.0000  CM
         REQUIRED MIN. MICROTUBE LENGTH =     50.0000  CM

  **************** THE ASSUMED LATERAL DIAMETER =    14.0000 MM ****************

         ENFEASIBLE SOLUTION , EITHER

         INCREASE THE LATERAL DIAMETER;
         INCREASE THE MICROTUBE DIAMETER;
         OR DECREASE THE MIN. MICROTUBRE LENGTH

STATEMENTS EXECUTED=     282
CORE USAGE       OBJECT CODE=   15680 BYTES,ARRAY AREA=    5600 BYTES,TOTAL AREA AVAILABLE=  971552  BYTES
DIAGNOSTICS        NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=       0
COMPILE TIME=     0.13 SEC,EXECUTION TIME=     0.02 SEC,      0.29.00     MONDAY        2 JAN 89     WATFIV - MAR 1980 V2L0
        C$STOP
```

Figure (A.10) Application on Case I

```
*************************************************************
*************   THE CLCULATIONS OF THE LATERAL # 1  ***************
*************************************************************

DISCHARGE AT EACH MICROTUBE     =    20.0000  L/H
THE HEAD AT THE ENTRANCE        =     7.0000  METER
THE MICROTUBE DIAMETER          =     1.5000  MM
NUMBER OF MICROTUBES            =    10  MICROTUBES
TOTAL DISCHARGE                 =   200.0000  L/H
TOTAL LATERAL PIPE LENGTHS      =    95.0000  METER
THE COIL DIAMETER               =    10.0000  CM
REQUIRED MIN. MICROTUBE LENGTH =    50.0000  CM

**************** THE ASSUMED LATERAL DIAMETER =   20.0000 MM ****************
```

	LAND SLOPE (M/M)	TOTAL HEAD (M)	NUMBER OF COILS	MIC. LENGTH (CM)
MICROTUBE # 1:	0.0000	6.9808	0	54.50986
MICROTUBE # 2:	0.0000	6.9536	0	54.29771
MICROTUBE # 3:	0.0000	6.9315	0	54.12509
MICROTUBE # 4:	0.0000	6.9140	0	53.98843
MICROTUBE # 5:	0.0000	6.9007	0	53.88409
MICROTUBE # 6:	0.0000	6.8934	0	53.82777
MICROTUBE # 7:	0.0000	6.8877	0	53.78270
MICROTUBE # 8:	0.0000	6.8833	0	53.74890
MICROTUBE # 9:	0.0000	6.8805	0	53.72636
MICROTUBE # 10:	0.0000	6.8790	0	53.71510

```
THE MAXIMUM PRESSURE HEAD =   6.9808 M
THE MINIMUM PRESSURE HEAD =   6.8790 M

THE MAXIMUM MICROTUBE LENGTH  =   0.5451 M
THE MINIMUM MICROTUBE LENGTH  =   0.5372 M


*************************************************************
************   THE CLCULATIONS OF THE  LATERAL # 2  **************
*************************************************************

DISCHARGE AT EACH MICROTUBE     =    20.0000  L/H
THE HEAD AT THE ENTRANCE        =     7.0000  METER
THE MICROTUBE DIAMETER          =     2.0000  MM
NUMBER OF MICROTUBES            =    10  MICROTUBES
TOTAL DISCHARGE                 =   200.0000  L/H
TOTAL LATERAL PIPE LENGTHS      =    95.0000  METER
```

Figure (A.11) Application on Case I

```
THE COIL DIAMETER                =    10.0000  CM
REQUIRED MIN. MICROTUBE LENGTH =    50.0000  CM

***************** THE ASSUMED LATERAL DIAMETER =    14.0000 MM ****************

              LAND SLOPE / TOTAL HEAD / NUMBER OF COILS / MIC.  LENGTH
                 (M/M)        (M)                            (CM)
MICROTUBE #  1:  0.0000       6.8991          4             183.09170
MICROTUBE #  2:  0.0000       6.7513          4             184.19850
MICROTUBE #  3:  0.0000       6.6310          4             180.51430
MICROTUBE #  4:  0.0000       6.5357          4             177.59780
MICROTUBE #  5:  0.0000       6.4630          3             175.37080
MICROTUBE #  6:  0.0000       6.4102          3             173.75230
MICROTUBE #  7:  0.0000       6.3861          3             173.01630
MICROTUBE #  8:  0.0000       6.3681          3             172.46430
MICROTUBE #  9:  0.0000       6.3561          3             172.09630
MICROTUBE # 10:  0.0000       6.3501          3             171.91230

 THE MAXIMUM PRESSURE HEAD =    6.8991 M
 THE MINIMUM PRESSURE HEAD =    6.3501 M

 THE MAXIMUM MICROTUBE LENGTH' =    1.8420 M
 THE MINIMUM MICROTUBE LENGTH  =    1.7191 M


  ************************************************************
************    THE CLCULATIONS OF THE  LATERAL # 3  **************
  ************************************************************

        DISCHARGE AT EACH MICROTUBE     =    20.0000  L/H
        THE HEAD AT THE ENTRANCE        =     7.0000  METER
        THE MICROTUBE DIAMETER          =     1.5000  MM
        NUMBER OF MICROTUBES            =    10  MICROTUBES
        TOTAL DISCHARGE                 =   200.0000  L/H
        TOTAL LATERAL PIPE LENGTHS      =    95.0000  METER
        THE COIL DIAMETER               =    10.0000  CM
        REQUIRED MIN. MICROTUBE LENGTH =    40.0000  CM

***************** THE ASSUMED LATERAL DIAMETER =    14.0000 MM ****************

              LAND SLOPE / TOTAL HEAD / NUMBER OF COILS / MIC.  LENGTH
                 (M/M)        (M)                            (CM)
MICROTUBE #  1:  0.0000       6.8991          0             53.87233
MICROTUBE #  2:  0.0000       6.7513          0             52.71780
MICROTUBE #  3:  0.0000       6.6310          0             51.77832
MICROTUBE #  4:  0.0000       6.5357          0             51.03461
```

Cont. Figure (A.11) Application on Case I

```
MICROTUBE #  5:   0.0000      6.4630          0           50.46675
MICROTUBE #  6:   0.0000      6.4102          0           50.05400
MICROTUBE #  7:   0.0000      6.3861          0           49.86632
MICROTUBE #  8:   0.0000      6.3681          0           49.72556
MICROTUBE #  9:   0.0000      6.3561          0           49.63173
MICROTUBE # 10:   0.0000      6.3501          0           49.58481

 THE MAXIMUM PRESSURE HEAD =   6.8991 M
 THE MINIMUM PRESSURE HEAD =   6.3501 M

 THE MAXIMUM MICROTUBE LENGTH  =   0.5387 M
 THE MINIMUM MICROTUBE LENGTH  =   0.4958 M


STATEMENTS EXECUTED=    1549
CORE USAGE       OBJECT CODE=   15680 BYTES,ARRAY AREA=    5600 BYTES,TOTAL AREA AVAILABLE=  832288  BYTES
DIAGNOSTICS        NUMBER OF ERRORS=        0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=      0
COMPILE TIME=    0.14 SEC,EXECUTION TIME=     0.06 SEC,      0.47.34    MONDAY        2 JAN 89    WATFIV - MAR 1980 V2L0
         C$STOP
```

Cont. Figure (A.11) Application on Case I

```
     ***************************************************************
  *************   THE CLCULATIONS OF THE LATERAL # 1  **************
     **************************************************************

            DISCHARGE AT EACH MICROTUBE     =   40.0000 L/H
            THE LATERAL DIAMETER            =   14.0000 MM
            THE MICROTUBE DIAMETER          =    2.0000 MM
            THE NUMBER OF MICROTUBES        =   10  MICROEUBES
            TOTAL DISCHARGE                 =  400.0000 L/H
            TOTAL LATERAL PIPE LENGTHS      =  105.0000 METER
            THE COIL DIAMETER               =    2.0000 CM
            REQUIRED MIN. MICROTUBE LENGTH =   50.0000 CM

                LAND SLOPE / TOTAL HEAD / NUMBER OF COILS / MIC.  LENGTH
                   (M/M)         (M)                             (CM)
   MICROTUBE #  1:  -0.0050       7.8161          2             66.13155
   MICROTUBE #  2:  -0.0050       7.2688          2             62.82381
   MICROTUBE #  3:  -0.0050       6.8141          1             60.35941
   MICROTUBE #  4:  -0.0050       6.4437          1             56.98769
   MICROTUBE #  5:  -0.0050       6.1491          0             55.98064
   MICROTUBE #  6:  -0.0050       5.9213          0             53.90678
   MICROTUBE #  7:  -0.0050       5.7510          0             52.35623
   MICROTUBE #  8:  -0.0050       5.6283          0             51.23894
   MICROTUBE #  9:  -0.0050       5.5542          0             50.56479
   MICROTUBE # 10:  -0.0050       5.4922          0             50.00011

    THE REQUIRED TOTAL HEAD AT THE LATERAL ENTRANCE  =   8.1879 METER


STATEMENTS EXECUTED=      477
CORE USAGE        OBJECT CODE=    15680 BYTES,ARRAY AREA=    5600 BYTES,TOTAL AREA AVAILABLE=  971552  BYTES
DIAGNOSTICS         NUMBER OF ERRORS=        0, NUMBER OF WARNINGS=        0, NUMBER OF EXTENSIONS=       0
COMPILE TIME=     0.15 SEC,EXECUTION TIME=     0.01 SEC,      0.29.10    MONDAY        2 JAN 89    WATFIV - MAR 1980 V2L0
        C$STOP
```

Figure (A.12) Application on Case II

```
    ************************************************************
*********    THE CLCULATIONS OF THE LATERAL # 1  **************
    ************************************************************

           THE HEAD AT THE ENTRERENCE  =     5.0000  METER
           THE LATERAL DIAMETER        =    14.0000  MM
           THE MICROTUBE DIAMETER      =     1.5000  MM
           TOTAL LATERAL PIPE LENGTHS  =   105.0000  METER
           THE COIL DIAMETER           =     2.0000  CM
           REQUIRED MIN. MICROTUBE LENGTH =   50.0000 CM

               LAND SLOPE / TOTAL HEAD / NUMBER OF COILS / MIC.  LENGTH
                  (M/M)          (M)                            (CM)
   MICROTUBE #  1:  -0.0050       4.9053           0            55.77246
   MICROTUBE #  2:  -0.0050       4.7537           0            54.04944
   MICROTUBE #  3:  -0.0050       4.6211           0            52.54146
   MICROTUBE #  4:  -0.0050       4.5057           0            51.22925
   MICROTUBE #  5:   0.0000       4.4557           0            50.66138
   MICROTUBE #  6:   0.0000       4.4315           0            50.38579
   MICROTUBE #  7:   0.0000       4.4121           0            50.16533
   MICROTUBE #  8:   0.0000       4.3976           0            49.99998
   MICROTUBE #  9:   0.0010       4.3979           0            50.00345
   MICROTUBE # 10:   0.0010       4.4030           0            50.06201

    DISCHARGE AT EACH MICROTUBE  =   16.1354 L/H


STATEMENTS EXECUTED=    1238
CORE USAGE        OBJECT CODE=   15680 BYTES,ARRAY AREA=    5600 BYTES,TOTAL AREA AVAILABLE=  971552  BYTES
DIAGNOSTICS         NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=       0
COMPILE TIME=     0.14 SEC,EXECUTION TIME=     0.02 SEC,      0.29.21    MONDAY        2 JAN 89    WATFIV - MAR 1980 V2L0
         C$STOP
```

Figure (A.13) Application on Case III

Figure (A.14a) Linear programming Formulation

```
min     107 x111 + 130 x112 + 207 x113
      + 107 x121 + 130 x122 + 207 x123
      + 107 x131 + 130 x132 + 207 x133
      + 107 x211 + 130 x212 + 207 x213
      + 107 x221 + 130 x222 + 207 x223
      + 107 x231 + 130 x232 + 207 x233
      + 107 x311 + 130 x312 + 207 x313
      + 107 x321 + 130 x322 + 207 x323
      + 107 x331 + 130 x332 + 207 x333
      + 130 x31  + 207 x32  + 350 x33
      + 130 x21  + 207 x22  + 350 x23
      + 107 x11  + 130 x12  + 207 x13
      + 100000.0 y1 + 121000.0 y2
      + 144000.0 y3 + 169000.0 y4
st
2)  y1 + y2 + y3 + y4 = 1
3) x111 + x112 + x113 = 100
4) x121 + x122 + x123 = 100
5) x131 + x132 + x133 = 100
6) x211 + x212 + x213 = 100
7) x221 + x222 + x223 = 100
8) x231 + x232 + x233 = 100
9) x311 + x312 + x313 = 100
10) x321 + x322 + x323 = 100
11) x331 + x332 + x333 = 100
12) x31 + x32 + x33 = 150
13) x21 + x22 + x23 = 150
14) x11 + x12 + x13 = 150
15) 10000y1+13000y2 + 16000y3 + 17000y4 - h0 = 0
16) 74x31+18.0x32+5.90x33 - hf3 = 0
17) h0-hf3>=7000
18) h0-hf3<=20000
19) 33.2x21+8.0x22+2.62x23-hf2= 00
20) h0-hf3-hf2<=20000
21) h0-hf3-hf2>=7000
22) 60.0x11+8.3x12+2.0x13 - hf1 =00
23) h0-hf3-hf2-hf1>= 7000
24) h0-hf3-hf2-hf1<= 20000
25) 60.0x331+8.3x332+2.0x333 - hf33 =000
26) h0-hf3-hf33>=6000
27) h0-hf3-hf33<=9000
28) 28.0x321+4.0x322+1.0x323 - hf32 =000
29) h0-hf3-hf33-hf32>=6000
30) h0-hf3-hf33-hf32<=9000
31) 7.80x311+1.1x312+0.25x313 - hf31 =000
32) h0-hf3-hf33-hf32-hf31>=6000
33) h0-hf3-hf33-hf32-hf31<=9000
34) 60.0x231+8.3x232+2.0x233 - hf23 =000
35) h0-hf3-hf2-hf23>=6000
36) h0-hf3-hf2-hf23<=9000
37) 28.0x221+4.0x222+1.0x223 - hf22 =000
38) h0-hf3-hf2-hf23-hf22>=6000
39) h0-hf3-hf2-hf23-hf22<=9000
40) 7.80x211+1.1x212+0.25x213 - hf21 =000
41) h0-hf3-hf2-hf23-hf22-hf21>=6000
42) h0-hf3-hf2-hf23-hf22-hf21<=9000
```

Cont. Figure (A.14a) Linear Programming Formulation


```
43) 60.0x131+8.3x132+2.0x133 - hf13 = 0
44) h0-hf3-hf2-hf1-hf13>=6000
45) h0-hf3-hf2-hf1-hf13<=9000
46) 28.0x121+4.0x122+1.0x223 - hf12 = 000
47) h0-hf3-hf2-hf1-hf13-hf12>=6000
48) h0-hf3-hf2-hf1-hf13-hf12<=9000
49) 7.80x111+1.1x112+0.25x113 - hf11 =000
50) h0-hf3-hf2-hf1-hf13-hf12-hf11>=6000
51) h0-hf3-hf2-hf1-hf13-hf12-hf11<=9000
53) x112 - 100 y112<=0
54) x121 - 100 y121<=0
55) x122 - 100 y122<=0
56) x131 - 100 y131<=0
57) x132 - 100 y132<=0
59) x212 - 100 y212<=0
60) x221 - 100 y221<=0
61) x222 - 100 y222<=0
62) x231 - 100 y231<=0
63) x232 - 100 y232<=0
65) x312 - 100 y312<=0
66) x321 - 100 y321<=0
67) x322 - 100 y322<=0
68) x332 - 100 y332<=0
69) x113 - 100 y113<=0
70) x123 - 100 y123<=0
71) x133 - 100 y133<=0
72) x213 - 100 y213<=0
73) x223 - 100 y223<=0
74) x233 - 100 y233<=0
75) x331 - 100 y331<=0
76) x313 - 100 y313<=0
77) x323 - 100 y323<=0
78) x333 - 100 y333<=0
79) y112+y121<=1
80) y113+y121<=1
81) y113+y122<=1
82) y122+y131<=1
83) y123+y131<=1
84) y123+y132<=1
85) y212+y221<=1
86) y213+y222<=1
87) y213+y221<=1
88) y222+y231<=1
89) y223+y231<=1
90) y223+y232<=1
91) y312+y321<=1
92) y313+y321<=1
93) y313+y322<=1
94) y322+y331<=1
95) y323+y331<=1
97) x12 - 150 y12 <= 0
98) x13 - 150 y13 <= 0
99) x21 - 150 y21 <= 0
100)x22 - 150 y22 <= 0
```

```
101)x23 - 150 y23 <= 0
102)x31 - 150 y31 <= 0
103)x32 - 150 y32 <= 0
104)x33 - 150 y33 <= 0
104)y12+y21<=1
105)y13+y21<=1
106)y13+y22<=1
107)y22+y31<=1
108)y23+y31<=1
109)y23+y32<=1
110)h0-hf3-h3=0
111)h0-hf3-hf2-h2=0
112)h0-hf3-hf2-hf1-h1=0
113)h0-hf3-hf33-h33=0
114)h0-hf3-hf33-hf32-h32=0
115)h0-hf3-hf33-hf32-hf31-h31=0
116)h0-hf3-hf2-hf23-h23=0
117)h0-hf3-hf2-hf23-hf22-h22=0
118)h0-hf3-hf2-hf23-hf22-hf21-h21=0
119)h0-hf3-hf2-hf1-hf13-h13=0
120)h0-hf3-hf2-hf1-hf13-hf12-h12=0
121)h0-hf3-hf2-hf1-hf13-hf12-hf11-h11=0
end
go
integer y1
integer y2
integer y3
integer y4
integer y12
integer y13
integer y21
integer y22
integer y23
integer y31
integer y32
integer y33
integer y112
integer y113
integer y121
integer y122
integer y123
integer y131
integer y132
integer y133
integer y212
integer y213
integer y221
integer y222
integer y223
integer y231
integer y232
```

```
integer y233
integer y312
integer y313
integer y321
integer y322
integer y323
integer y331
integer y332
integer y333
```

Cont. Figure (A.14a) Linear Programming Formulation

Figure (A.14b) Linear Programming Computer Output

	327093.	1.00000	F	.100000E+31
Y2	.000000	-61614.7	I	1.00000
Y3	.000000	-121229.	I	1.00000
Y4	.000000	-123768.	I	1.00000
Y12	1.00000	.000000	I	1.00000
Y13	.000000	-12662.4	I	1.00000
Y21	.000000	.000000	I	1.00000
Y22	1.00000	.000000	I	1.00000
Y23	1.00000	.000000	I	1.00000
Y31	.000000	.000000	I	1.00000
Y32	.000000	.000000	I	1.00000
Y33	1.00000	.000000	I	1.00000
Y112	1.00000	.000000	I	1.00000
Y113	.000000	.000000	I	1.00000
Y121	.000000	.000000	I	1.00000
Y122	1.00000	-2811.11	I	1.00000
Y123	.000000	.000000	I	1.00000
Y131	.000000	.000000	I	1.00000
Y132	1.00000	.000000	I	1.00000
Y133	1.00000	.000000	I	1.00000
Y212	.000000	.000000	I	1.00000
Y213	.000000	.000000	I	1.00000
Y221	1.00000	.000000	I	1.00000
Y222	1.00000	.000000	I	1.00000
Y223	.000000	.000000	I	1.00000
Y231	.000000	-4441.67	I	1.00000
Y232	1.00000	-7096.25	I	1.00000
Y233	1.00000	.000000	I	1.00000
Y312	.000000	.000000	I	1.00000
Y313	.000000	.000000	I	1.00000
Y321	1.00000	.000000	I	1.00000
Y322	1.00000	.000000	I	1.00000
Y323	1.00000	.000000	I	1.00000
Y331	.000000	-4441.67	I	1.00000
Y332	1.00000	-7096.25	I	1.00000
Y333	.000000	.000000	I	1.00000
X111	.000000	58.8889	C	.100000E+31
X112	100.000	.000000	C	.100000E+31
X113	.000000	66.6111	C	.100000E+31
X121	.000000	242.222	C	.100000E+31
X122	100.000	.000000	C	.100000E+31
X123	.000000	.000000	C	.100000E+31
X131	.000000	608.889	C	.100000E+31
X132	46.0317	.000000	C	.100000E+31
X133	53.9683	.000000	C	.100000E+31
X211	100.000	.000000	C	.100000E+31
X212	.000000	16.5792	C	.100000E+31
X213	.000000	92.7646	C	.100000E+31
X221	9.79167	.000000	C	.100000E+31
X222	90.2083	.000000	C	.100000E+31
X223	.000000	86.3472	C	.100000E+31
X231	.000000	.000000	C	.100000E+31
X232	100.000	.000000	C	.100000E+31
X233	.000000	.000000	C	.100000E+31
X311	100.000	.000000	C	.100000E+31

X312	.000000	16.5792	C	.100000E+31
X313	.000000	92.7646	C	.100000E+31
X321	46.0417	.000000	C	.100000E+31
X322	53.9583	.000000	C	.100000E+31
X323	.000000	74.1250	C	.100000E+31
X331	.000000	.000000	C	.100000E+31
X332	100.000	.000000	C	.100000E+31
X333	.000000	.000000	C	.100000E+31
X31	.000000	1655.35	C	.100000E+31
X32	.000000	190.213	C	.100000E+31
X33	150.000	.000000	C	.100000E+31
X21	.000000	592.814	C	.100000E+31
X22	88.6617	.000000	C	.100000E+31
X23	61.3383	.000000	C	.100000E+31
X11	.000000	1301.64	C	.100000E+31
X12	150.000	.000000	C	.100000E+31
X13	.000000	.000000	C	.100000E+31
Y1	1.00000	.000000	C	.100000E+31
H0	10000.0	.000000	C	.100000E+31
HF3	885.000	.000000	C	.100000E+31
HF2	870.000	.000000	C	.100000E+31
HF1	1245.00	.000000	C	.100000E+31
HF33	830.000	.000000	C	.100000E+31
HF32	1505.00	.000000	C	.100000E+31
HF31	780.000	.000000	C	.100000E+31
HF23	830.000	.000000	C	.100000E+31
HF22	635.000	.000000	C	.100000E+31
HF21	780.000	.000000	C	.100000E+31
HF13	490.000	.000000	C	.100000E+31
HF12	400.000	.000000	C	.100000E+31
HF11	110.000	.000000	C	.100000E+31
H3	9115.00	.000000	C	.100000E+31
H2	8245.00	.000000	C	.100000E+31
H1	7000.00	.000000	C	.100000E+31
H33	8285.00	.000000	C	.100000E+31
H32	6780.00	.000000	C	.100000E+31
H31	6000.00	.000000	C	.100000E+31
H23	7415.00	.000000	C	.100000E+31
H22	6780.00	.000000	C	.100000E+31
H21	6000.00	.000000	C	.100000E+31
H13	6510.00	.000000	C	.100000E+31
H12	6110.00	.000000	C	.100000E+31
H11	6000.00	.000000	C	.100000E+31

Cont. Figure (A.14b) Linear Programming Computer Output