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CALCULATION OF THE PRESSURE RISE IN THE CHL 5000 GALLON LIQUID HELIUM DEWAR

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1. INTRODUCTION

The writing of a computer program to calculate the pressure rise in the CHL 5000 gallon dewar was motivated by the writing of a Fermilab engineering note on the safety of the dewar which is presently being installed at the Fermilab Central Helium Liquefier. The calculation is intended to verify that the pressure in the inner vessel will not rise above a safe level in a catastrophic venting situation.

The inner vessel holds 5000 gallons of Liquid Helium. It is 22 ft long and 7 ft in diameter. The cylindrical shell and torispherical heads are made of 304 SS 5/16 inches thick. The vessel has a liquid nitrogen cooled shield and is perlite insulated. The vessel is designed to stand a 50 psi differential pressure on the inner vessel. A typical way to size reliefs on large dewars is to use the assumption that the insulating vacuum space is filled with helium gas and calculate the conduction heat load in the helium vessel. Thsi is the procedure required by the Department of Transportation document GSA S-13. This calculation is straight forward and yields a heat load of 646 watts for the 5000 gallon dewar, based on perlite insulation filled with helium gas 1 atm.

The question arises, however, what if a major rupture of the outer shell occurs and liquid air condenses on the inner shell? Preliminary estimates indicate that the heat load in this case would be of the order of 500 KW. Furthermore, vent rates are required which make small pressure drop formulas invalid in a typical 3" size vent pipe.

Therefore, the calculation was done in detail including calculations of the helium film coefficients, temperature drop across the stainless steel shell, and the nitrogen condensing coefficients. In addition, the flow in the vent pipe was calculated including considerations of acceleration of the gas, Fanno flow in the vent pipe, and choking at the end of the vent pipe.

The following assumptions are made as input to the calculation:

1) Nitrogen gas is condensing on the shell at $77^{o}K$. Effects of Nitrogen freezing were neglected.
2) The temperature and pressure in the inner vessel were assumed uniform.
3) Appropriate papers in the literature were used to determine the helium heat transmission coefficients and the nitrogen condensing coefficients. These are discussed in more detail later.
4) The flow in the vent pipe is large enough to bring the pressure at the exit of the vent pipe to 1.5 atm. absolute or to bring the gas velocity to sonic speed, whichever occurs at a lower flow.
5) A separate program called STACK was written to verify that the pressure drop in the external vent stack does not contribute to the pressure in the dewar. The calculation techniques in STACK are very similar to PD 5000, and the result of running STACK is that pressure drops in the external vent stack chosen are not significant.
6) Heat input in the vent pipe was neglected. This is justified on account of the very large flow, about 50 Kg/sec. and the short pipe, 36" long. The gas velocity is typically 40m/sec.
7) Helium properties were interpolated from National Bureau of Standards bulletin NBS 631. The program was written in FORTRAN IV and runs on the Fermilab CYBER computer in interactive mode from a terminal. Typical running times are 3 minutes for a complete pressure temperature history. One minute runs can be linked.

2. BASIC PROGRAM LOGICAL FLOW

The program is on a CYBER permanent disc file and is called PD 5000, a memonic for "pressure in the 5000 gallon dewar". The calculation sequence is as follows:

1) The main program reads and prints input data and loads variables from talbes.
2) The main program calls subroutine FLUX to get initial heat flux. FLUX has numerous printouts.
3) The main program calls PIPE which calculates mass flow, and prints assorted information about the flow in the vent pipe.
4) Having mass flow and heat flux, the main program calculates a new pressure and temeprature, after a time increment DT.
5) The main program calls FLUX and PIPE again to update mass flow and heat flux with new pressure and temperature in dewar.
6) The program loops in MAIN back to step 4 until time limit is reached which generates a STOP.

Fig. 1 shows the system components schematically.

3. DETAILS OF THE VARIOUS CALCULATIONS

The simpler subroutines will be discussed first.

1) Subroutine TABLE 1, COND, VISTAB, STAIN are merely a series of DATA statements that load thermodynamic variables from table entries. They load variable arrays for enthalpy, specific volume, entropy, sonic velocity, thermal conductivity, viscosity, and thermal conductivity of stianless steel.
2) Subroutine SINTRP(L,XT,YT,X,Y). - This is a single linear interpolation. L is a variable diemnsion input argument equal to the number of X and Y entries. XT and YT are the input table of X and Y values, and are 1 dimensional arrays with L entries. X is the independent input variable, and Y is the output dependent variable. The X entries must be non-decreasing. IF X is outside the range, it extrapolates linearly. This routine is called form PTI2 and FLUX.

3) Subroutine DINTRP (L,M,ZT,XT,YT,X,Y,Z). - This is a double lienar interpolation with variable dimensions, L for X and M for Y. ZT is a two dimensional array of dependent variable entries as a function of X and Y. XT is the one dimensional array of X entries of dimension L and YT is a similar array of Y entries of dimension M. X and Y entries must both be nondecreasing. Inputs are L,M,ZT,XT,YT. The output is Z, the interpolated dependent variable. This subroutine is called from MAIN, FLUX, and PIPE.

4) Subroutine PT12 (V,H,ZVOL,ZH,PT,TT,P,T) inputs:

V specific volume in NBS 631 table units, 100cc/g

H enthalpy in NBS 631 table units, = J/g.

ZVOL Table of specific volume entries, table units. Dimensions are 45 temperature entries from 3.5^{o}K to 40^{o}K and 15 pressure entries from 1.2 atm to 4.0 atm.

ZH enthalpy entries similar to ZVOL in J/g.

PT pressure entries in atm (15)

TT temperature entries in degrees Kelvin.

Outputs

P pressure in atm corresponding to V and H.

T temperature in degrees Kelvin corresponding to V and H.

This subroutine constructs various one dimensional arrays of corresponding independent and dependent variables and performs single interpolations to find the pressure and temperature corresponding to the input specific volume and enthalpy. No starting values are needed, since the subroutine checks all table entries in the range 3.5 to 40^{o}K and 1.2 to 4 atm. It has only 14 fortran statements, but it has fairly long running in DO loops. Note that the NBS 631 table units for specific volume, V and ZVOL, are 100 cc/gm

5) Main Program - This part of the program calculates the changes in pressure and temperature in the dewar and passes this information to FLUX and PIPE. It uses the heat flux $\dot{Q}$ and the man flow W calculated in FLUX and PIPE respectively. It also increments the time variable and does various bookkeeping chores.

Initially the program reads in the initial conditions and the data on the vent pipe. It starts out knowing W, flow starting value kg/sec. This value must be less than the solution or the program will print very small X for distance down the pipe and an output flow which is the same as the starting value and larger than the correct solution. Other inputs are:

PØ initial dewar pressure; atm.

TØ initial dewar temperature, K

XL length of the vent pipe inches

D diameter of the vent pipe inches

WR a reset on flow so that PIPE can step up flow to the solution on successive calls, kg/sec.

WSTEP flow step size used in PIPE, kg/sec.

DT time increment, sec.

TL time limit, sec. used to generate a STOP

START starting time, sec. used in linking successive runs.

T1 Starting value for outisde temperature of the shell

T2 starting value for inside temeprature of the shell

The calculation goes as follows:

(1) Use DINTRP to calculate initial V and H at PØ, TØ.

(2) Call Flux for initial $\dot{Q}$, W/M^2

(3) Change to total heat flux $\dot{Q}=\dot{Q}xA$, A=surface area = 44.3 M^2

(4) Numerical integration of V and H.

Increase in $V = \int_i^f \frac{VdM}{M}$, Increase in $H = \int_i^f \frac{\dot{Q}}{M} dT$

where

dM = Wdt = decrease in Mass in dT,

dT = time increment, sec.

i = initial state

f = final state

M = mass of fluid remaining kg.

W = mass flow out, kg/sec.

(5) Use updated V and H to calculate updated PØ and TØ. These are calculated by subroutine PT12 described above.

(6) The process of incrementing time, V, H continue until TIME = TL(limit) then the program stops.

The main program writes the current values suitable for an input tape (TAPE 5) on tape 7, which can be transferred to tape 5 for a linked run by an interactive statement, R, TAPE 7, Binary program (rewind)
RENAME, TAPE 5 = TAPE 7.

The various printouts from MAIN, PIPE, and FLUX are written on the terminal (OUTPUT) and on TAPE 6, which can accumulate linked runs if you do not rewind it.

6) Subroutine FLUX(T1I, T2I, TØ, PØ, T1, T2, QDOT)

(1) Inputs:

T1I Temperature of outside of shell, K, starting value

T2I temperature of inside of shell, K, starting value

TØ temperature of bulk fluid in dewar,

PØ pressure of bulk fluid in dewar, atm

(2) Outputs:

T1 calculated temperature of outside of shell, K

T2 calculated temperature of inside of shell, K

QDOT calculated heat flux, W/m^2

(3) Calculating Sequence

This subroutine calculates the net heat flux to the bulk fluid and the temperatures of both sides of the stainless steel shell. The iterative calculation proceeds as follows, all units are MKS, deg K.

a. Assume T1 + T2 starting values T1I, T2I and $\dot{Q} = 0$, starting value

b. Calcualte

$$h_n,\ h_1,\ \bar{R}_s = \int_{T_2}^{T1} k_s(T)\, dT \times \frac{1}{T2-T1}$$

c. Calculate the overall heat transfer coefficient U

$$U = \frac{h_1\, h_n\, \bar{k}_s}{h_n\, \bar{k}_s + h_1\, \bar{k}_s + L\, h_1\, h_n}$$

d. Calculate the heat flux $\dot{Q}$ in W/m^2

$$\dot{Q} = UA\ (77.\ ^{o}K - T\emptyset),\ A = 1m^2$$

e. Calculate new values of T1, T2

$$T1 = 77. - \frac{\dot{Q}}{h_n A}$$

$$T2 = T\emptyset + \frac{\dot{Q}}{h_1 A}$$

f. Check change in $\dot{Q}$. If the fractional change in $\dot{Q}$ is greater than 10^{-5}, replace T1 and T2 with new value, and go back to step b, and repeat step b through f. If $\dot{Q}$ does not change more than the criterion, exit the loop, print results, and return to MAIN.

(4) Discussion of film coefficients.

The nitrogen coefficients were taken from McAdams[1] and are of the form

$$h_n = .725\ \left(\frac{k_f^{\,3}\, \rho_f^{\,3}\, g\lambda}{D\, \mu\, \Delta T}\right)^{\frac{1}{4}} \qquad (1)$$

These were in BTU, hr, ft, lb. system and the result was converted to MKS. This coefficient was checked against a recent experimental result published by Ewald and Perroud [4]. This experiment measured heat transfer by condensing nitrogen films under similar conditions to the dewar problem. The symbols in eqn (1) are as follows:

k_f thermal conductivity of film

p_f density of film

g gravitutional acceleration

λ heat of vaporization

D shell diameter

μ viscosity

ΔT temperature drop across the film.

The helium film coefficients for natural convection were determined using the correlations established by Deev et al[1]. This experiment was performed with a range of temperature, pressures, and heat fluxes very similar to those encountered in the dewar problem. After the code was written, calculations were run at points measured in the paper, and the agreement was good.

The correlations of Deev are now described. The basic heat transfer is correlated in terms of the dimensional groups called Neuselt's number, Nu and Rayleigh's number Ra defined as follows:

$$Nu = \frac{h_1 D}{k}$$

Nu - Nusselt's number

D - Diameter of vessel or height of plate

k - thermal conductivity of bulk fluid.

$$Ra = \frac{g\ D^3\ Cp\ \rho^2 \beta\ \Delta T}{\mu k}$$

where

Ra = Rayleigh's number

Cp = heat capacity at constant pressure

ρ = fluid density

β = volumetric coefficient of thermal expansion

ΔT = T2 - T$\emptyset$

μ = viscosity

k = thermal conductivity

Deev et al. evaluate the various parameters at the bulk temeprature and account for the rapid variation of properties in the conduction film by calculating the "simplexes"

$\frac{\bar{C}p}{C_\infty}$ and $\frac{\rho_w}{\rho_\infty}$ w refers to the inner wall and ∞ refers to the bulk fluid.

$\bar{C}p$ = mean heat capacity = $\frac{h_w - h_\infty}{\Delta T}$

The film coefficient is the calculated from the correlation[2]

$$N_\mu = .135(Ra)^{1/3} (\bar{C}p/C_\infty)^n (\frac{\rho_w}{\rho})^{.5} \quad (2) = .135(Ra)^{1/3} (\frac{cp}{c_\infty})^n (\frac{Pn}{P_\infty})^{.5}$$

The exponent n is dependent on whether the temperature is above or below the so called "psuedo critical temperature", Tm, at which the heat capacity has a sharp maximum. Other parameters such as sonic velocity and β have minima or maxima here. This temperature is slightly higher than the true critical temperature, 5.2^oK, and it varies with pressure. For example, at 3 atm, $Tm = 5.6^oK$.

The prescription for n in equation (2) is as follows:

for $T \leq Tm$, $n = .5$

for $T > Tm$, $n = 1.0$

it should be noted that the correlation is insensitive to the vertical dimension D since it cancels out of relation (2).

7) Subroutine PIPE (W, PT1, TT1, WSTEP, PSTEP, XL, D1, TØ, PØ, NSTEP, PSTEP, PMIN, DRAG)

(1) Inputs

W - starting value for flow, pg/sec

PT1 - atm starting value for pressure at vent pipe inlet

TT1 - K starting value for temperature at vent pipe inlet

WSTEP- Flow step size used in approaching a solution kg/sec

PSTEP- Determines step size in inner loops to find solution in nozzle entry and in integrating the pressure drop through the vent pipe, dimensionless.

XL - vent pipe length, inches

DL - vent pipe diameter inches

TØ - dewar temperature, K

PØ - dewar pressure, atm

NSTEP - step size in nozzle, dimensionless

DRAG - Fanno friction coefficient, dimensionless

PMIN - Pressure criterion at end of vent pipe, atm.

(2) Outputs

W, PT1 and TT1 are modified and passed back to MAIN.

PT1 and TT1 are the pressure and temperature after the fluid has accelerated to enter the pipe.

(3) Method of calculation.

The basic thermodynamics for the flow process is described in a book by Zucrow[5]. The method is to step parameters in loops and test for the solution at each step. The main loop is to step W from a starting value until the pipe exit meets one of two conditions;

I The pressure is PMIN or less

II The gas velocity is sonic or greater.

When one of these conditions is met, the program prints the results at the current time and returns to MAIN.

On the way to the pipe exit, the program goes through two successive closed loops within the main W loop. The first loop is called NOZZLE and accounts for acceleration on entering the vent pipe. The second loop, called PIPE starts from this solution and integrates the pressure drop up the pipe.

(a) NOZZLE LOOP

The first loop approximates the temperature and pressure after the fluid has accelerated to the flow W in the vent pipe. This is accomplished by satisfying the following relations;

$H = Ho + \frac{G^2V^2}{2}$ energy balance

$S = So$, Ho = dewar specific enthalpy

H = enthalpy solution

G = mass velocity = W/A

A = pipe cross sectional area

So = Dewar entropy

S = Entropy at solution

Vo = specific volume in dewar

V = specific volume at solution in nozzle

The calculation sequence is as follows:

(a) Calculate the current HØ, VØ, SØ using DINTRP and the input PØ, TØ. Various conversions are made from table units to MKS during the calculation and will not be noted in detail.

(b) Compute enthalpy step dH

dH = HØ/NSTEP

(c) Compute mass velocity

G = W/A

(d) Start out with H approximated by

$H = Ho - \frac{G^2Vo^2}{2}$

(e) Set X = 0 = initialization for integration up the pipe

(f) Enter the nozzle loop here

Increment H

H = H + dH

(g) Adjust V to maintain energy balance

$V = \sqrt{\frac{2(Ho - H)}{G^2}}$

(h) Compute new P, T from V and H using subroutine PT12

(i) Compute S using DINTRP and P, T.

(j) S is increasing as the solution is approached, so compare S to So. This imposes the entropy condition. If S<So, go to step f, and continue incrementing H. If S $\geq$ So, the solution has been reached, so exit the nozzle loop.

At this point, T, P, H, V have values appropriate for the fluid in the vent pipe after it has been accelerated. The calculation now maintains energy and momentum balance in the fluid and includes the effects to the frictional drag forces on the mementum balance as the fluid moves up the pipe. The appropriate energy balance equation is:

$$H = Ho - \frac{G^2V^2}{2,}$$

In this region of flow, the friction coefficient changes very slowly, and is assumed to be constant at DRAG. The momentum balance equation is;

Outlet

$$\int \frac{dP}{V} + G^2\left(\ln \frac{V2}{V1} + \frac{1}{2} \cdot \frac{4\,DRAG}{D}\right)$$

Inlet

Where L = pipe length

V2 = specific volume at outlet

V1 = specific volume at inlet

D = pipe diameter

PIPE LOOP

This calculation proceeds as follows:

a) Compute step size dH = Ho/PSTEP

b) Continue stepping H down from H at nozzle exit.

c) Enter PIPE LOOP

increment H

H = H - dH

d) Adjust V to maintain energy balance

$$V = \sqrt{\frac{2(Ho - H)}{G^2}}$$

e) Compute new pressure and temperature from V and H using subrouting PT12

f) Accumulate contribution to trapezoidal integration of $\frac{dP}{V}$

g) Compute fluid velocity VEL

$$VEL = G \cdot V$$

h) Compute sonic velocity, VS, using DINTRP and P, T.

i) Check readiness to exit the PIPE loop by checking whether

$$P \leq PMN$$

$$VEL \geq VS$$

If either of these conditions is met, proceed to next step, otherwise loop back to step C and continue incrementing H.

j) Exit pipe loop. Compute X = distance up the pipe corresponding to the current P and T.

$$X = \int \frac{dP}{V} + G^2 \left(\ln \frac{V2}{V1} + \frac{2\,D}{DRAG}\right)$$

k) Compare X to XL (actual pipe length). If X > XL this indicates that W is too small to establish the specified limiting velocity or pressure in a length XL. Therefore, loop back to nozzle loop with

$$W = W + WSTEP$$

If $X \leq XL$, then the last step in W met the conditions imposed, and the current P, T, W etc. are the correct values. Print results and return to MAIN, which will continue incrementing time etc.

4. RESULTS OF COMPUTER RUNS OF PROGRAM PD5000

Computer runs of the program were made using various values of the vent pipe diameter, pressure at the end of the vent pipe, and drag coefficient. The initial pressure was chosen as 3.0 atm corresponding to the burst disc setting. The initial temperature, $4.84^{o}K$ corresponds to a condition which started with the

dewar full of saturated liquid at 1 atm which subsequently rises in pressure to 3 atm on the input of heat. Fig. 3 shows a typical pressure history generated by the program. The calculations covered 81.7 seconds after the disc burst. Note that initially the pressure drops rapidly while the fluid is very dense. As the fluid warms, the pressure begins to rise and reaches a maximum of 3.46 atm at 44 seconds. It then drops continuously until at 82 seconds, it has reached a pr ire of 2.43 atm. At this time, only 8.3% of the initial fluid remains in the dewar. Note that during this history, no phase separation occurs in the dewar. The drag coefficinet chosen, f = .009, corresponds to drawn tubes, which is the type of vent pipe used. As this run developed, the flow became limited by sonic velocity, shortly after the maximum pressure was attained, and then dropped below sonic as the dewar pressure diminished.

Another run was with a drag coefficient of f = .0146 corresponding to commercial steel pipes. This gave a very similar curve with a maximum pressure of 3.53, which is only 2% higher than the curve for f = .009. This indicates that the maximum pressure is not strongly sensitive to the drag coefficient in this range of values. In order to establish a minimum pipe size which will hold the dewar pressure at some level, runs of the program were made with diameters of 3.0 inches and 4.0 inches. These are shown in Fig. 4. The pressure reaches 4 atm and is still rising rapidly in 20 seconds for the 3 in. pipe. For the 4 in. pipe the pressure has a maximum near 4 atm. and the flow becomes sonic near to the point of maximum pressure.

The actual vent pipe installed in the dewar was a 4.5 OD seamless 304 stainless steel tube with $\frac{1"}{16}$ wall thickness, giving an inside diameter of 4.375 corresponding to the plot in Fig.3.

Figures 5 through 8 show the results of PD 5000 for heat flux, flow, dewar temperature, and gas velocity under the same conditions as Fig. 3.

5. REFERENCES

1) McAdams, W.H., "Heat Transmission", McGraw Hill, New York, 1954

2) Kontratenko, A.K., et. al., 6th International Heat Transfer Conference, Toronto 1978, 2, p 205, paper NC4.

3) "Handbook on Materials for Superconducting Machinery", Metals and Ceramics Information Center, Battelle Columbus Laboratories, 1974 Publication MCIC-HB-04

4) Ewald, R., and Perroud, P., Advances in Cryogenic Engineering, 16, Plenum Pres New York (1971), p. 475

5) Zucrow, J.J., and Hoffman, J.D., "Gas Dynamics" Vol. 1, John Wiley & Sons Inc., New York (1976)

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FIG. 1.- SCHEMATIC ILLUSTRATION OF GEOMETRY AND PARAMETERS

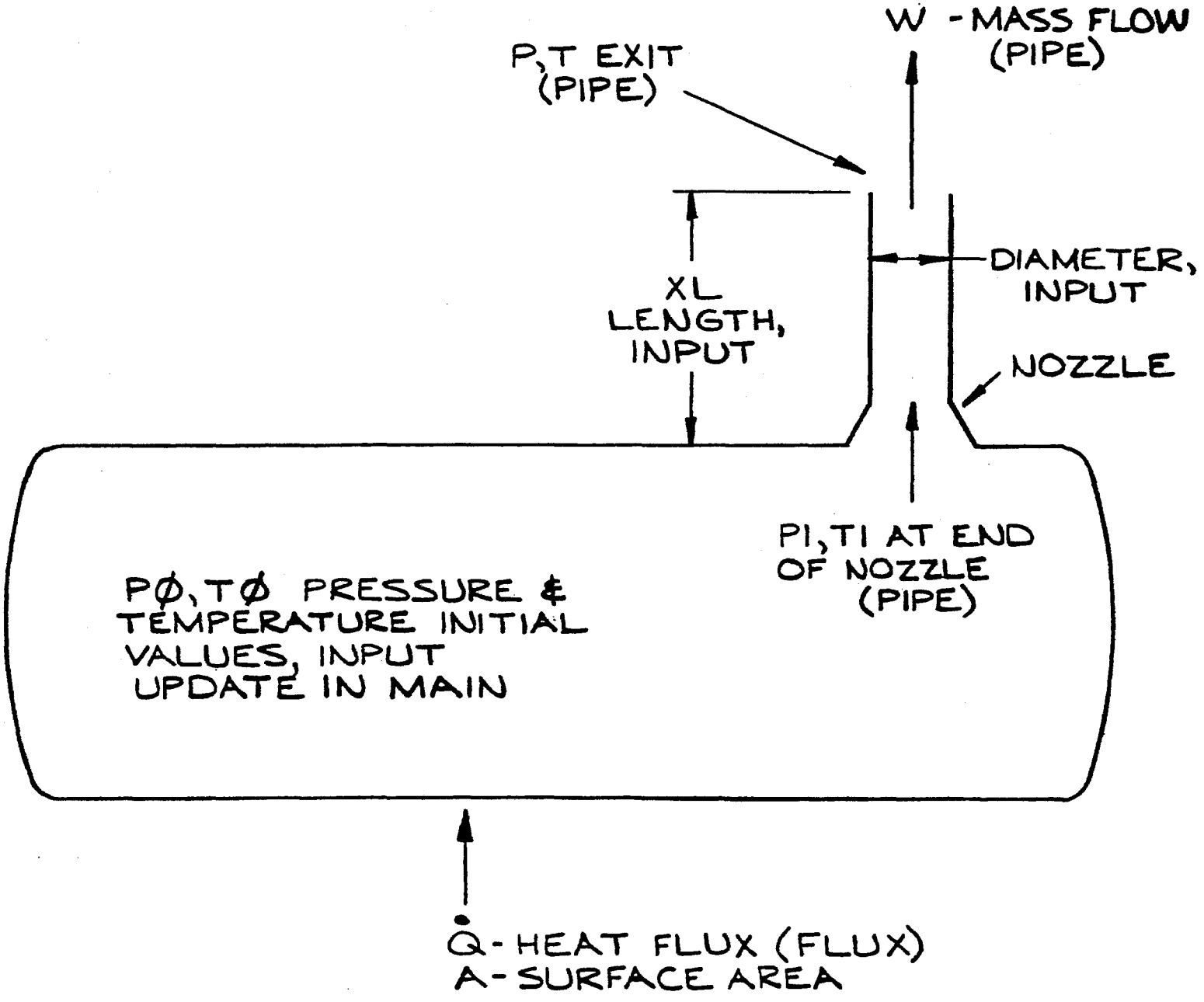

FIG. 2.- SUBROUTINE FLUX ILLUSTRATION

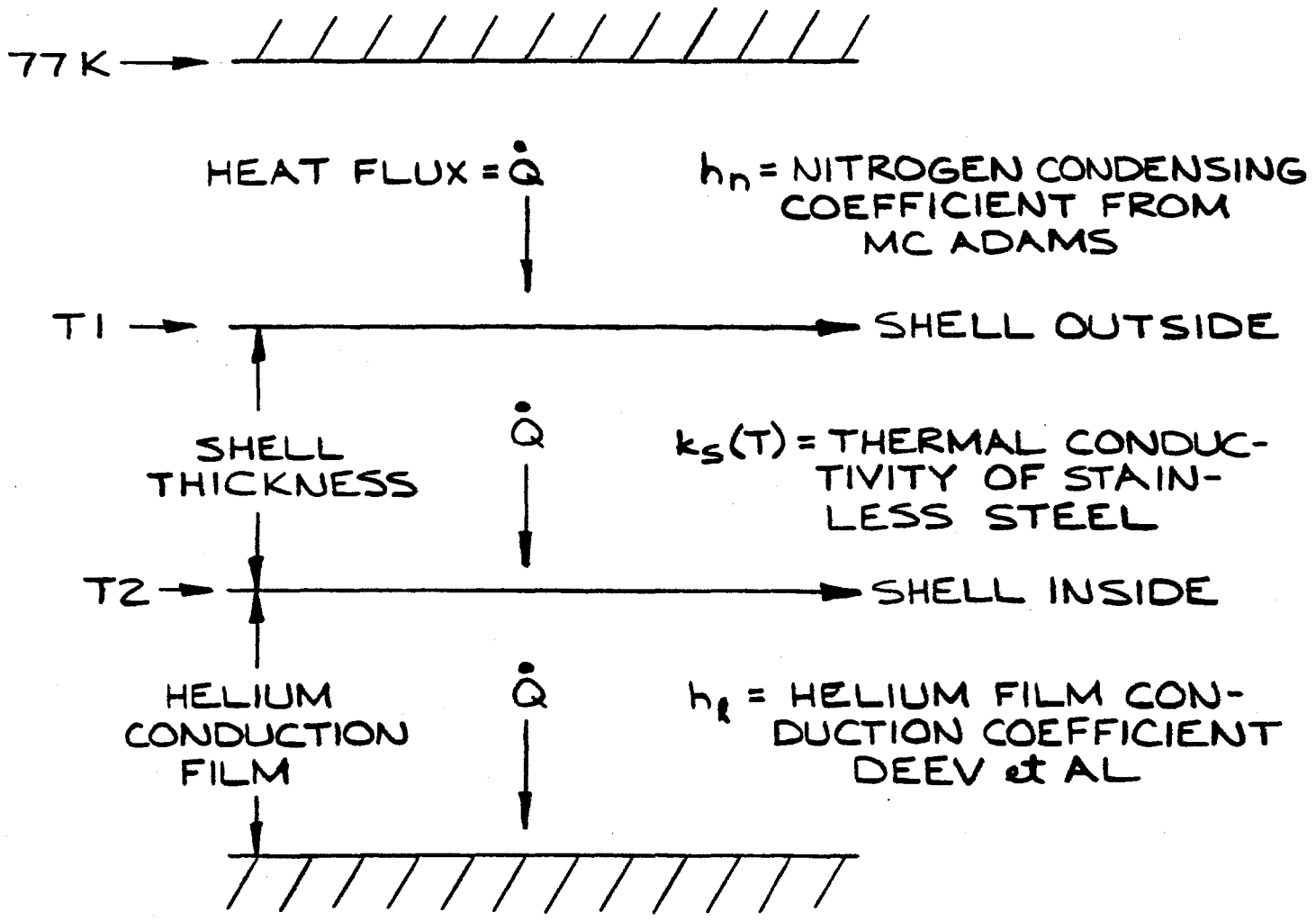

FIG 3 PMIN = 1.5 DRAG = .009

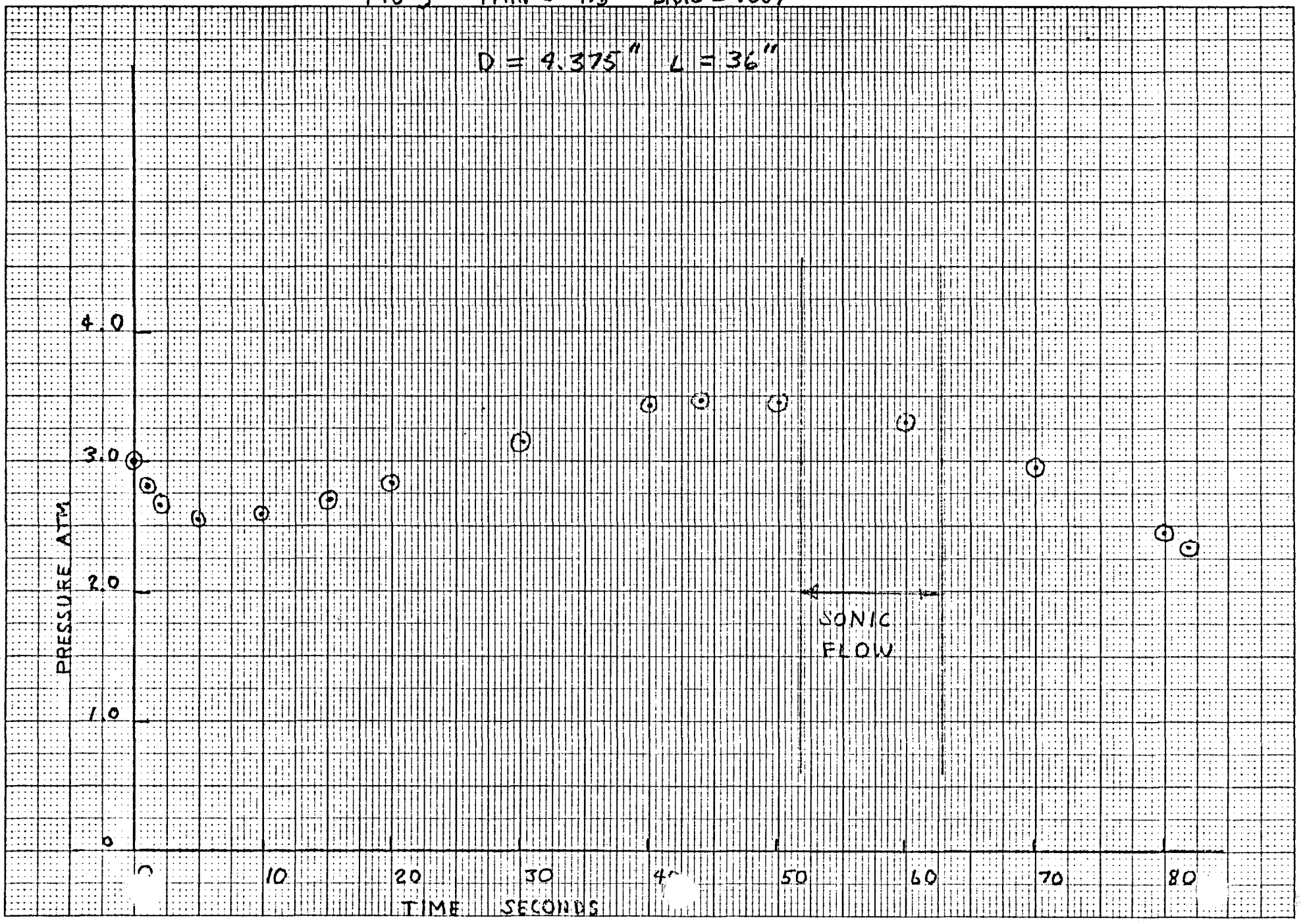

FIG 4 PRESSURE DEVELOPMENT FOR U = 5.0 AND D = 1.0

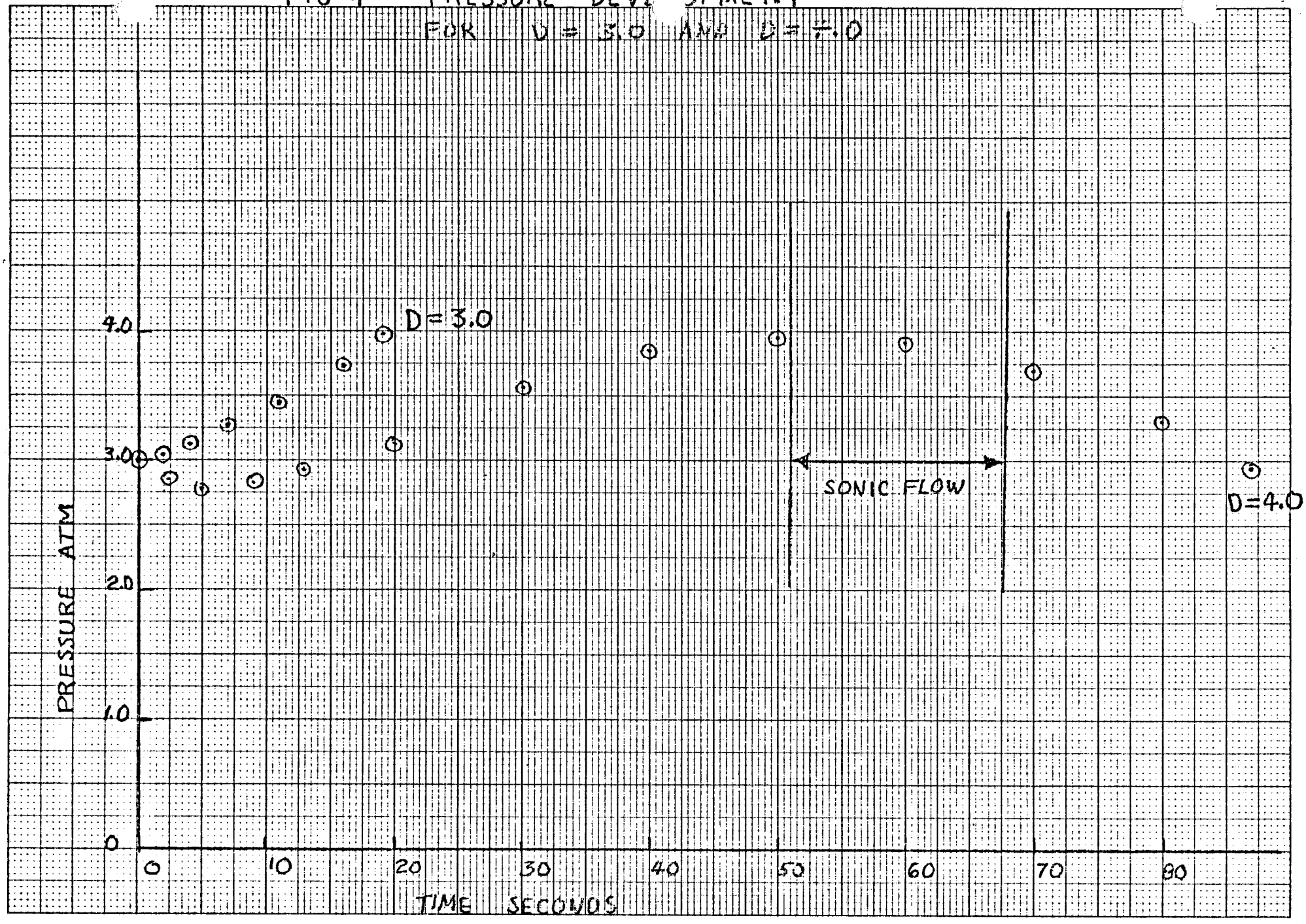

FIG. 5

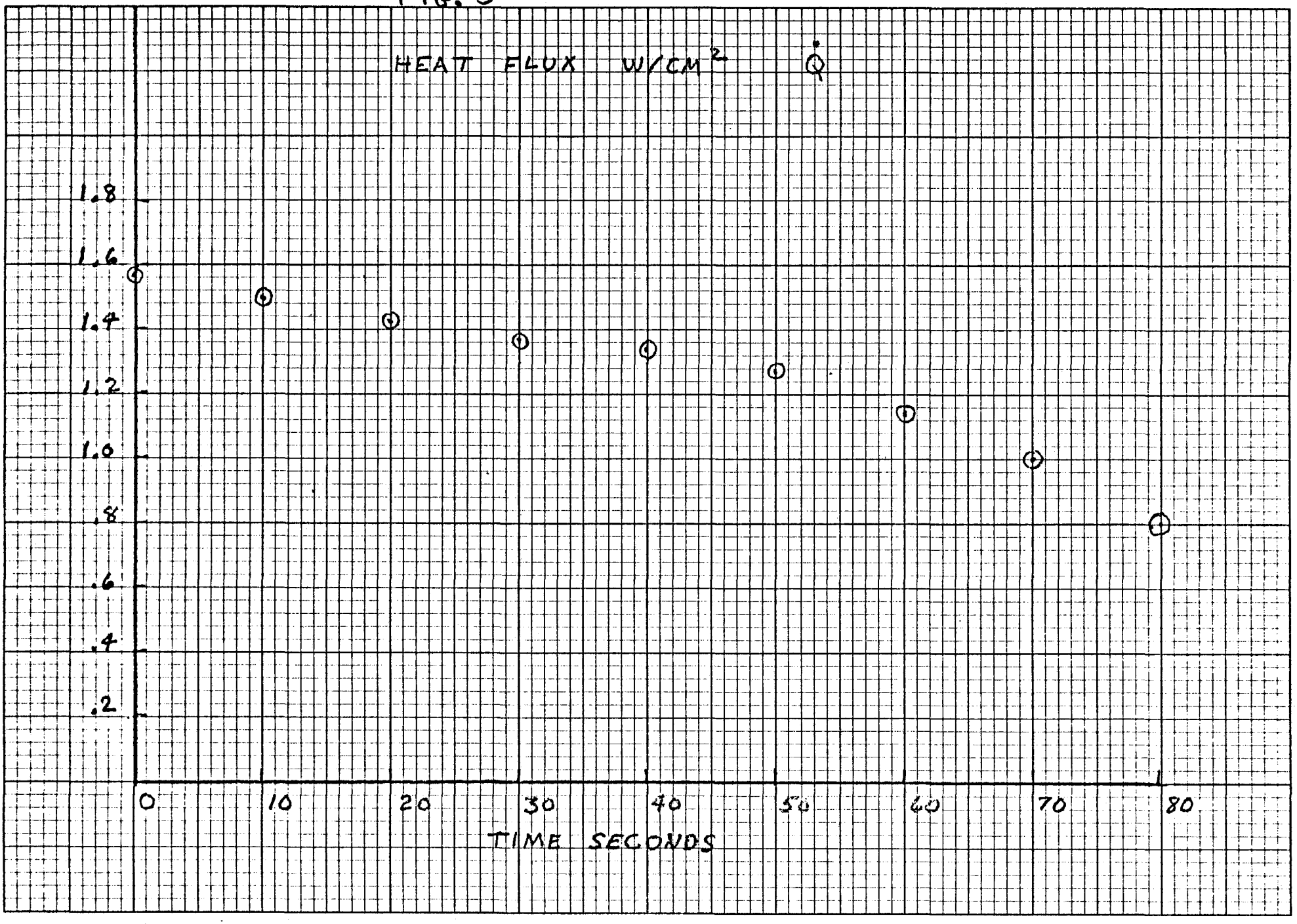

FIG. 6

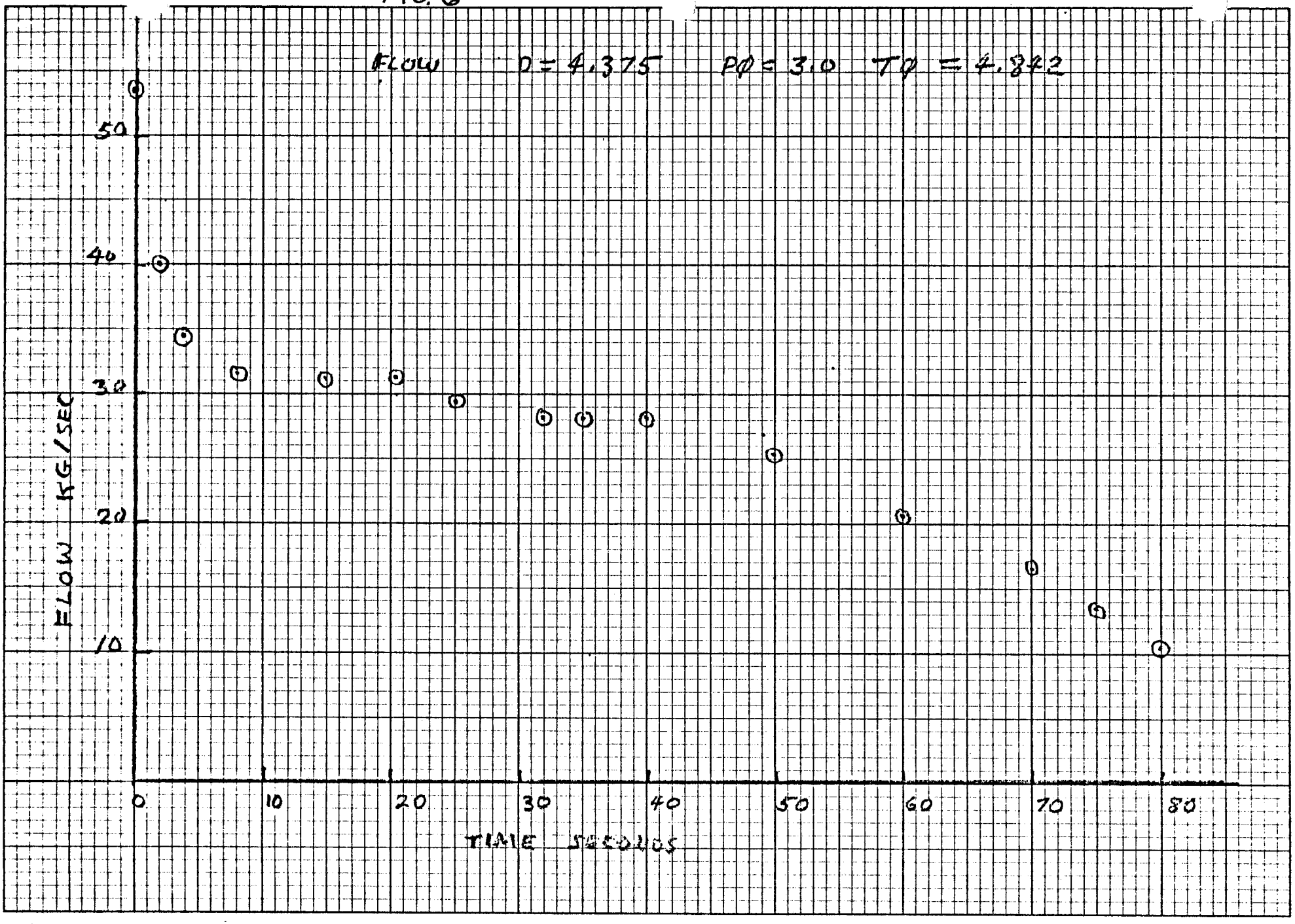

FIG. 7

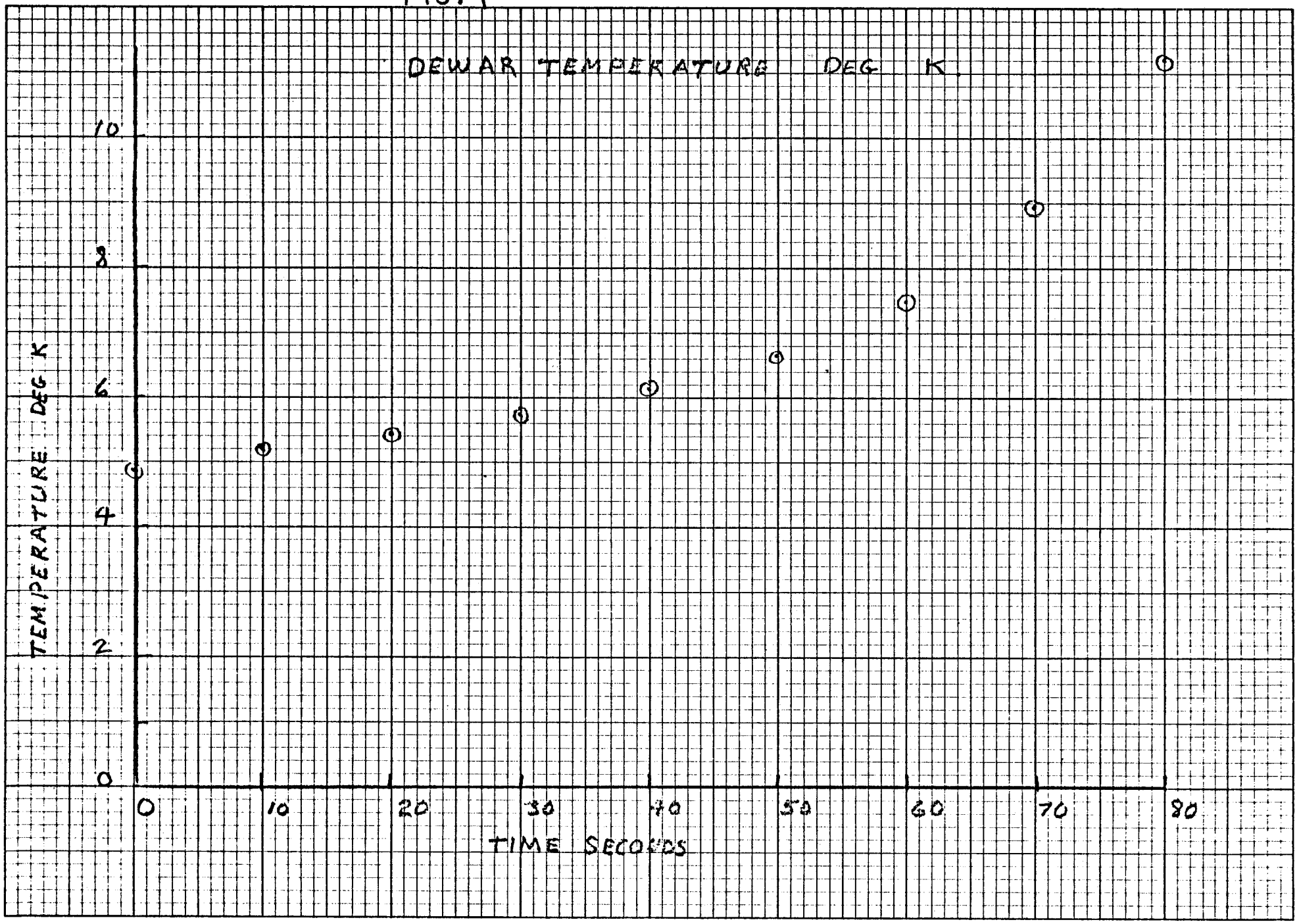

FIG. 8