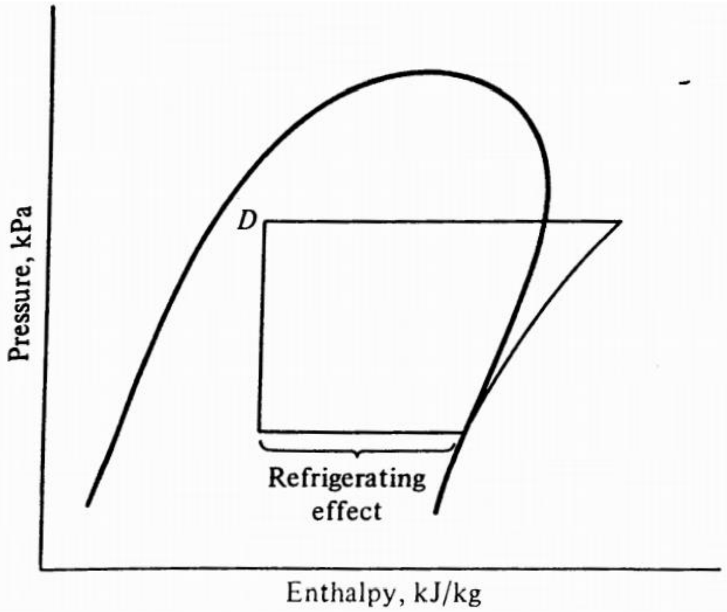


Figure 13-3 Reduction in refrigerating effect when some vapor enters the capillary tube.

3. Advantages and disadvantages of capillary tube

Capillary tubes have certain advantages and disadvantages.
Their advantages are summarized below;

1. Predominant enough to give them universal acceptance in factory-sealed systems.
2. They are simple, have no moving parts, and are inexpensive.
3. They also allow the pressures in the system to equalize during the off cycle.
4. The motor driving the compressor can then be one of low starting torque.

The disadvantages of capillary tubes are summarized below;

1. They are not adjustable to changing
2. Load conditions, are susceptible to clogging by foreign matter, and require the mass of
3. Refrigerant charge to be held within close limits

This last feature has dictated that the capillary tube be used only on hermetically sealed systems, where there is less likelihood of the refrigerant leaking out. The capillary tube is designed for one set of operating conditions, and any change in the applied heat load or condensing temperature from design conditions represents a decrease in operating efficiency.

Analytical computation of pressure drop in a capillary tube

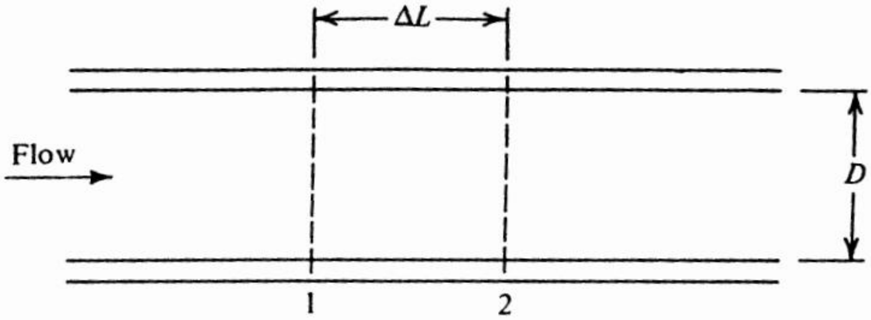


Figure 13-4 Incremental length of capillary tube.

The equations relating states and conditions at points I and 2 in a very short length of capillary tube in Fig. 13-4 will be written using the following notation:

A = cross-sectional area of inside of tube, m^2
D = ID of tube, m
f = friction factor, dimensionless
h = enthalpy, kJ/kg
h_f = enthalpy of saturated liquid, kJ/kg
h_g = enthalpy of saturated vapor, kJ/kg
ΔL = length of increment, m
p = pressure, Pa
Re = Reynolds number = $VD/\nu\mu$
ν = specific volume, m^3/kg
ν_f = specific volume of saturated liquid, m^3/kg
ν_g = specific volume of saturated vapor, m^3/kg
V = velocity of refrigerant, m/s
w = mass rate of flow, kg/s
x = fraction of vapor in mixture of liquid and vapor
μ = viscosity, Pa · s
μ_f = viscosity of saturated liquid, Pa · s
μ_g = viscosity of saturated vapor, Pa · s

The fundamental equations applicable to the control volume bounded by points 1 and 2 in Fig. 13-4 are (1) conservation of mass, (2) conservation of energy, and (3) conservation of momentum.

The equation for conservation of mass states that

$$w = \frac{V_1 A}{v_1} = \frac{V_2 A}{v_2} \tag{13-1}$$

or

$$\frac{w}{A} = \frac{V_1}{v_1} = \frac{V_2}{v_2} \tag{13-2}$$

and w/A will be constant throughout the length of the capillary tube.

The statement of conservation of energy is

$$1000h_1 + \frac{V_1^2}{2} = 1000h_2 + \frac{V_2^2}{2} \tag{13-3}$$

which assumes negligible neat transfer in and out of the tube.

The momentum equation in words states that the difference in forces applied to the element because of drag and pressure difference on opposite ends of the element equals that needed to accelerate the fluid

$$\left[(p_1 - p_2) - f\frac{\Delta L}{D}\frac{V^2}{2v}\right]A = w(V_2 - V_1) \tag{13-4}$$

As the refrigerant flows through the capillary tube, its pressure and saturation temperature progressively drop and the fraction of vapor x continuously increases. At any point

$$h = h_f(1 - x) + h_g x \tag{13-5}$$

and

$$v = v_f(1 - x) + v_g x \tag{13-6}$$

In Eq. (13-4) V, v, and f all change as the refrigerant flows from point 1 to point 2, but some simplification results from Eq. (13-2), which shows that V/v is constant so that

$$f\frac{\Delta L}{D}\frac{V^2}{2v} = f\frac{\Delta L}{D}\frac{V}{2}\frac{w}{A} \tag{13-7}$$

In the calculation to follow in Example 13-1 the V used in Eq. (13-7) will be the mean velocity

$$V_m = \frac{V_1 + V_2}{2} \tag{13-8}$$

Since expressing the friction factor f for the two-phase flow is complex, we shall use an approximation and later compare the calculation with experimental results as a check on the validity of this approximation as well as of any other approximation built into the method.

For Reynolds numbers in the lower range of the turbulent region an applicable equation for the friction factor f is

$$f = \frac{0.33}{\text{Re}^{0.25}} = \frac{0.33}{(VD/\mu v)^{0.25}} \tag{13-9}$$

The viscosity of the two-phase refrigerant at a given position in the tube is a function of the vapor fraction x

$$\mu = \mu_f(1 - x) + \mu_g x \tag{13-10}$$

The mean friction factor f_m applicable to the increment of length 1-2 is

$$f_m = \frac{f_1 + f_2}{2} = \frac{0.33/\text{Re}_1^{0.25} + 0.33/\text{Re}_2^{0.25}}{2} \tag{13-11}$$

13-5 Calculating the length of an increment The essence of the analytical calculation method is to determine the length of the increment 1-2 in Fig. 13-4 for a given reduction in saturation temperature of the refrigerant. The flow rate and all the conditions at point 1 are known, and for an arbitrarily selected temperature at point 2 the remaining conditions at point 2 and the ΔL will be computed in the following specific steps:

1. Select t_2.
2. Compute p_2, h_{f2}, h_{g2}, v_{f2}, and v_{g2}, all of which are functions of t_2.
3. Combine the continuity equation (13-2) and the energy equation (13-3)

$$1000h_2 + \frac{v_2^2}{2}\left(\frac{w}{A}\right)^2 = 1000h_1 + \frac{V_1^2}{2} \tag{13-12}$$

Substitute Eqs. (13-5) and (13-6) into Eq. (13-12)

$$1000h_{f2} + 1000(h_{g2} - h_{f2})x + \frac{[v_{f2} + (v_{g2} - v_{f2})x]^2}{2}\left(\frac{w}{A}\right)^2 = 1000h_1 + \frac{V_1^2}{2} \tag{13-13}$$

Everything in Eq. (13-13) is known except x, which can be solved by the quadratic equation

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{13-14}$$

where
$$a = (v_{g2} - v_{f2})^2 \left(\frac{w}{A}\right)^2 \frac{1}{2}$$

$$b = 1000(h_{g2} - h_{f2}) + v_{f2}(v_{g2} - v_{f2}) \left(\frac{w}{A}\right)^2$$

$$c = 1000(h_{f2} - h_1) + \left(\frac{w}{A}\right)^2 \frac{1}{2} v_{f2}^2 - \frac{V_1^2}{2}$$

4. With the value of x known, h_2, v_2, and V_2 can be computed.
5. Compute the Reynolds number at point 2 using the viscosity from Eq. (13-10), the friction factor at point 2 from Eq. (13-9), and the mean friction factor for the increment from Eq. (13-11).
6. Finally, substitute Eqs. (13-7) and (13-8) into Eq. (13-4) to solve for ΔL.

Ammar Abdulkadhim
E-mail: AmmarAbdulkadhim@uomus.edu.iq

Problem. 1: What length of capillary tube (ID = 1.63 mm) will drop the pressure of saturated liquid refrigerant 22 at 40°C to the saturation temperature of the evaporator of 5°C? The flow rate is 0.010 kg/s.

Use the following formula;

$$\ln\left(\frac{p}{1000}\right) = 15.06 - \frac{2418.4}{t + 273.15} \qquad (13\text{-}15)$$

$$v_f = \frac{v_f}{1000} = \frac{0.777 + 0.002062t + 0.00001608t^2}{1000} \qquad (13\text{-}16)$$

$$v_g = \frac{-4.26 + 94050(t + 273.15)/p}{1000} \qquad (13\text{-}17)$$

$$h_f = 200.0 + 1.172t + 0.001854t^2 \qquad (13\text{-}18)$$

$$h_g = 405.5 + 0.3636t - 0.002273t^2 \qquad (13\text{-}19)$$

$$\mu_f = 0.0002367 - 1.715 \times 10^{-6}t + 8.869 \times 10^{-9}t^2 \qquad (13\text{-}20)$$

$$\mu_g = 11.945 \times 10^{-6} + 50.06 \times 10^{-9}t + 0.2560 \times 10^{-9}t^2 \qquad (13\text{-}21)$$

Conditions at entrance to capillary tube, point 1 The entering refrigerant is saturated liquid at 40°C, and with $x = 0$ the properties from Eqs. (13-15) to (13-21) are

$p_1 = 1{,}536{,}000$ Pa $\quad v_1 = v_{f1} = 0.000885\ m^3/kg$
$h_1 = h_{f1} = 249.9$ kJ/kg $\quad \mu = \mu_{f1} = 0.0001823$ Pa • s

$$\frac{w}{A} = \frac{0.010}{\pi(0.00163^2)/4} = 4792.2\ kg/s \cdot m^2$$

$$V_1 = \frac{w}{A}v_1 = 4.242 m/s$$

$$Re_1 = 42{,}850 \qquad f_1 = \frac{0.33}{Re_1^{0.25}} = 0.0229$$

Conditions at point 2 Arbitrarily select $t_2 = 39°C$. Then

$p_2 = 1{,}498{,}800$ Pa $\quad h_{f2} = 248.5$ kJ/kg $\quad h_{g2} = 416.2$ kJ/kg
$v_{f2} = 0.000882\ m^3/kg \quad v_{g2} = 0.01533\ m^3/kg$
$\mu_{f2} = 0.0001833$ Pa • s $\quad \mu_{g2} = 0.00001429$ Pa • s

From Eq. (13-14)

$x = 0.008$

From Eqs. (13-5) and (13-6) and using an equation of the same form for viscosity, we get

$h_2 = 249.84$ kJ/kg $\quad v_2 = 0.0009952$ m^3/kg
$\mu_2 = 0.0001820$ Pa $\circ$ s

The following terms can now be calculated:

$$V_2 = \frac{w}{A} v_2 = 4.769 \text{ m/s} \qquad Re_2 = 42{,}923$$

$$f_2 = \frac{0.33}{42{,}923^{0.25}} = 0.0229$$

$$f_m = \frac{0.0229 + 0.0229}{2} = 0.0229$$

$$V_m = \frac{4.242 + 4.769}{2} = 4.506$$

From Eq. (13-4) the magnitude of the expression

$$f_m \frac{\Delta L}{D} \frac{V_m}{2} \frac{V}{v}$$

is found to be 34,964, and when the known values are substituted,

$$\Delta L_{1-2} = 0.2306 \text{ m}$$

Table 13-1 Capillary-tube calculations in Example 13-1

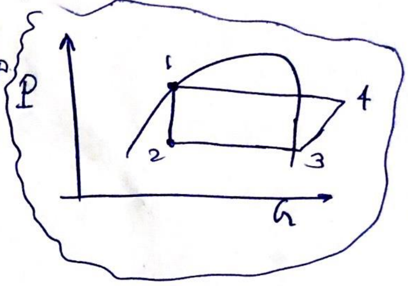
Position	Temperature, °C	Pressure, kPa	x	Specific volume, m^3/kg	Enthalpy, kJ/kg	Velocity, m/s	Increment length, m	Cumulative length, m
1	40	1536.4	0.000	0.000885	249.85	4.242		
2	39	1498.8	0.008	0.000995	249.84	4.769	0.2306	0.231
3	38	1461.9	0.016	0.001110	249.84	5.320	0.2013	0.432
4	37	1425.8	0.023	0.001230	249.84	5.895	0.1770	0.609
5	36	1390.3	0.031	0.001355	249.83	6.496	0.1565	0.765
6–31	...	...	...	...	...	...	...	...
32	9	657.65	0.194	0.007660	249.18	36.71	0.0097	2.089
33	8	637.90	0.199	0.008048	249.11	38.57	0.0085	2.098
34	7	618.61	0.204	0.008452	249.03	40.51	0.0075	2.105
35	6	599.78	0.209	0.008873	248.95	42.52	0.0066	2.112
36	5	581.38	0.213	0.009309	248.86	44.61	0.0049	2.118

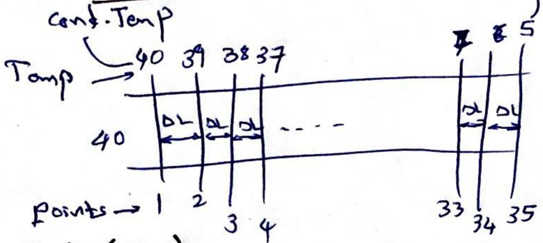
Details solution for the first two points had been inserted below;

Ammar Abdulkadhim
E-mail: AmmarAbdulkadhim@uomus.edu.iq

Example: What the length of capillary tube (I.D = 1.63 mm) will drop the pressure of saturated liquid refrigerant R-22 at 40 °C to the saturation temperature of the evaporator of 5 °C. Take the fluid flowrate as 0.010 Kg/sec.

Solution





Section (1-2):

Momentum eq: $\left[(P_1 - P_2) - f\frac{\Delta L}{D}\frac{V^2}{2v}\right] A = \dot{m}(V_2 - V_1)$

should be Calculated

* The pressures can be easily calculated from Refrigerant R-22 tables]

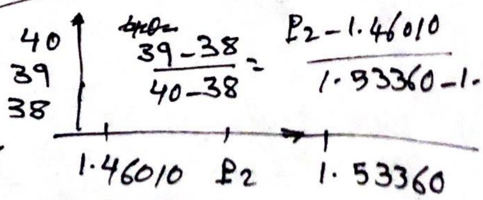
so: From table:

at $T_1 = 40\,^\circ C \rightarrow P_1 = 1.53360$ MPa

$P_1 = 1.5336 \times 10^6$ Pa

$T_2 = 39\,^\circ C \rightarrow P_2 = 1.49685 \times 10^6$ Pa

From Interpolation as illustrated here



$\frac{39-38}{40-38} = \frac{P_2 - 1.46010}{1.53360 - 1.46010} \rightarrow P_2$:

Page. No. 1

Friction factor; $f_m = \frac{f_1 + f_2}{2}$

Velocity; $V_m = \frac{V_1 + V_2}{2}$

Sp. Volume: $v_m = \frac{v_1 + v_2}{2}$

For point 1:

For Turbulent Flows: $f_1 = \frac{0.33}{Re_1^{0.25}}$

$$Re_1 = \frac{\rho_1 D V_1}{\mu_1} = \frac{D V_1}{v_1 \mu_1}$$

$D = 1.63$ mm

$V_1 \rightarrow \dot{m}_1 = \rho_1 V_1 A = \frac{V_1 A}{v_1}$

$$A = \frac{\pi}{4} D^2 = \frac{\pi}{4}(1.63 \times 10^{-3})^2$$

$\therefore A = 2.08672438 \times 10^{-6}$ m^2

$\dot{m} = \frac{V_1 A}{v_1}$; $v_1 = v_{f_1}(1 - x_1) + v_g x_1$

$x_1 = 0$ (because state 1 lies at the sat. point)

$\rightarrow v_1 = v_{f_1} = \frac{1}{\rho_{f_1}} = \frac{1}{1128.5} =$

$\therefore v_1 = 8.861320337 \times 10^{-4}$ m^3/kg

In this way, V_1 can be calculated as:

page. No. 2

$$\dot{m} = \frac{V_1 A}{\nu_1} \rightarrow \dot{m}\,\nu_1 = V_1 A$$

$$V_1 = \frac{\dot{m}\,\nu_1}{A} = \frac{(0.010)(8.86132 * 10^{-4})}{2.086724 * 10^{-6}}$$

$$\therefore V_1 = 4.246521688 \text{ m/s}$$

Two-Phase Dynamics Viscosity can be calculate:

$$\mu_1 = \mu_f (1 - \cancel{x_1}^{0}) + \mu_g \cancel{x_1}^{0}$$

$$\mu_1 = \mu_f = 139.4\,\mu Pa.s = 139.4 * 10^{-6}\, Pa.s$$

$$\therefore Re_1 = \frac{D V_1}{\nu_1 \mu_1} = \frac{1.63 * 10^{-3} * 4.2465}{8.86132 * 10^{-4} * 139.4 * 10^{-6}}$$

$$\therefore Re_1 = 56035.04913$$

$\because Re_1 > 2300$; then the fluid flow within the capillary tube will be turbulent

Thus; $f_1 = \dfrac{0.33}{Re^{0.25}} = \dfrac{0.33}{(56035.04913)^{0.25}}$

$$\therefore f_1 = 0.021448602 5$$

page. No. 3

E-mail: AmmarAbdulkadhim@uomus.edu.iq

For point 2

Since point 2 lies in the Mixture (Two-phase) region, it will be necessary to find out "x_2"

$$x_2 = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$a = (v_{g2} - v_{f2})^2 \left(\frac{\dot{m}}{A}\right)^2 \left(\frac{1}{2}\right)$$

From table at $T_2 = 39°C$

$v_{f2} = 0.88048 * 10^{-3}\ m^3/kg$

$v_{g2} = 15.5375 * 10^{-3}\ m^3/kg$

$a = 2466.784353$

$$b = 1000\,(h_{g2} - h_{f2}) + v_{f2}\,(v_{g2} - v_{f2}) \left(\frac{\dot{m}}{A}\right)^2$$

From Table: at $T_2 = 39°C$

$h_{g2} = 416.388\ kJ/kg$.

$h_{f2} = 248.361\ kJ/kg$.

$\therefore b = 168,323.3705$

$$c = 1000\,(h_{f2} - h_1) + \left(\frac{\dot{m}}{A}\right)^2 \frac{1}{2} v_{f2}^2 - \frac{V_1^2}{2}$$

$c = -1289.114561$

Page. No.4

In this way; $X_2 = 0.008$

$\therefore \forall_2 = \forall_{f_2}(1-x_2) + \forall_{g_2} x_2$

$= 0.88048 * 10^{-3}(1-0.008) + \frac{15.5375}{10^3} * 0.008$

$\forall_2 = 9.977 * 10^{-4}\ m^3/kg$

$\mu_2 = \mu_{f_2}(1-x_2) + \mu_g x_2$

$= 0.0001820\ Pa.s$

$h_2 = h_{f_2}(1-x_2) + x_2 h_{fg_2}$

$h_2 = 249.84\ kJ/kg$

Since the Mass is Conserved,

$\dot{m}_2 = \dot{m}_1 = 0.01 = \rho_2 V_2 A = \frac{V_2 A}{\forall_2}$

$\therefore V_2 = \frac{\dot{m}\ \forall_2}{A} = 4.769\ m/s$

$Re_2 = \frac{\rho_2 D V_2}{\mu_2} = \frac{D V_2}{\forall_2 \mu_2}$

$Re_2 = 42923$

Part No 5

$$f_2 = \frac{0.33}{Re_2^{0.25}} = 0.0229$$

$$f_{m(1-2)} = \frac{0.021 + 0.0229}{2}$$

$$= 0.0229$$

$$V_m = \frac{4.242 + 4.769}{2} = 4.506$$

From Eq. 13-4 by substitution the above calculated values:

$$\Delta L_{1-2} = 0.2306\,m$$

and use the same procedure with the others sections in order to find out ΔL_{2-3}, ΔL_{3-4} — — till we reach $T_{evap} = 5^\circ C$ by summing all of ΔL

see the lecture to find the table of 13-1

page No.8