IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 11, Issue 1 Ver. III (Jan. 2014), PP 79-85
www.iosrjournals.org

Phase Change Pressure Drop in Capillary of a Domestic Refrigerator

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Abstract: *This paper analyses the pressure drop for a single phase compressible and incompressible fluid flow and also a flow with phase change through a pipe or tube considering the existing theories of diffèrent pressure head drops. But the analysis on momentum gain pressure drop applicable for adiabatic capillary design of domestic refrigerators introduced some contradictions with universally accepted property values of refrigerant tables. This paper is based on flow properties of refrigerant R-600a through the capillary tube causing the expansion from the condenser pressure to the evaporator pressure with partial phase change from liquid to vapor by flash vaporisation. Here a more realistic theoretical concept is developed considering a new internal boosting force generated from the release of internal energy in the momentum balance relation and eliminates the contradiction in momentum gain pressure drop .This paper emphatises on the momentum gain caused by the internal energy réalèse rather than pressure drop in case of adiabatic flow with phase change.*

Keywords: *Adiabatic capillary tube, frictional pressure drop, internal boosting force , momentum pressure drop, viscous resistance.*

I. INTRODUCTION

Almost all fluid mechanic Workers have more or less knowledge of pressure difference between upstream and downstream of a single phase fluid flow system. Here the pressure does not fall suddenly from upstream to downstream, rather drops gradually through the flow system based on different factors. Lagrange and Euler had analyzed the fundamental flow kinematics to determine the velocity profile & acceleration in a flow system. Also Euler, Newton, stoke etc had analyzed the flow on mass, momentum and energy balance principle. Bernoulli used the Euler's momentum relation and developed his popular energy equation for non-viscous incompressible flow through a pipe. Here the pressure drop is contributed to momentum or kinematic energy and potential energy gain. Then stroke, Darcy & Fanning introduced the concept of viscous flow fluid friction and developed their separate relations for pressure drop which is shared in overcoming the friction, momentum and potential energy gain. Here the momentum analysis on single phase flow considers pressure force, weight force, viscous shear force and momentum gain force. But flow with phase change needs the consideration of an additional internal boosting force along with above common forces. Here this internal boosting force arises due to the release of internal stored energy as in combustion process of IC engines.

A thorough analysis of pressure drop due to the flow of refrigerants through expansion devices like adiabatic capillary tubes with phase change, using the concepts and theoretical relations of the paper by Ali Hussein 2008[1] , Mikol, E. P. *{1963)[2].* and other common references, the results were found to contradict with universally accepted experimental data collected from property table of refrigerants. So the phase change pressure drop leads to involve the complicated momentum and energy balance equations on a control volume analysis with some modifications in this paper.

II. Pressure drop concept for non viscous single phase flow through a tube or pipe

Always a steady flow analysis through equation of continuity and pressure drop is analyzed through momentum and energy analysis. Generally the flow pressure force drop is balanced with rate of momentum gain, gravitational force and other possible forces acting on the flow control volume and is known as momentum balance equation. Again the work done by the pressure drop is balanced with the momentum or kinetic energy, potential energy gain and is known as energy balance equation.

For steady one dimensional single phase flow in x-direction the continuity equation can be written as

$$\frac{\partial}{\partial x}(\rho \upsilon) = 0 \qquad (1)$$

For both compressible and incompressible flow in general, ignoring the fluid friction or viscous resistance Euler's momentum balance equation can be written as

$$\frac{\partial p}{\partial x} + g\frac{\partial}{\partial x}(\rho Z) + \upsilon\frac{\partial}{\partial x}(\rho\upsilon) = o$$

$$\partial p + g\partial(\rho z) + v\partial(\rho v) = 0 ---------------- (2)$$

For incompressible flow ρ = constant

$$-\partial p = \rho g\partial z + \rho v\partial v ---------------------- (3)$$

This shows the pressure force drop is used to overcome gravitation & gain of acceleration. The integration of the above momentum equation-3 gives the Bernoulli total energy equation at any section.

$$\therefore p + \rho gz + \frac{1}{2}\rho v^2 = const ---------------- (4)$$

Considering a flow control volume as in fig-1, the equation can be written as following.

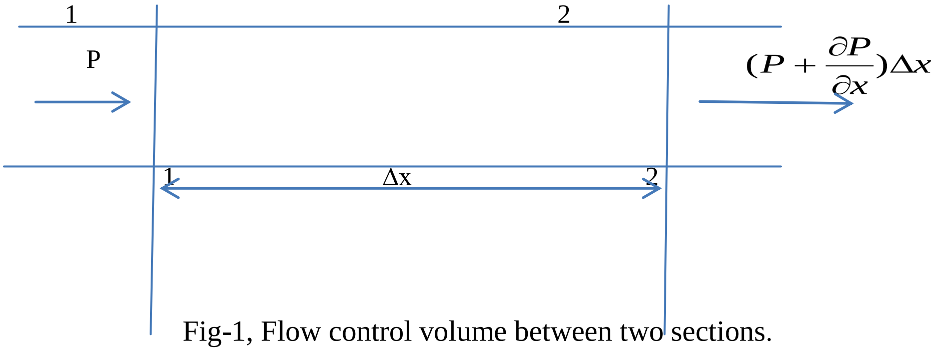

Fig-1, Flow control volume between two sections.

$$p_1 + \rho_1 g z_1 + \frac{1}{2}\rho_1 v_1^2 = p_2 + \rho_2 g z_2 + \frac{1}{2}\rho_2 v_2^2$$

$$\Rightarrow (p_1 - p_2) = \frac{1}{2}(\rho_2 v_2^2 - \rho_1 v_1^2) + g(\rho_2 z_2 - \rho_1 z_1)$$

This shows that the pressure energy drop is used in gain of potential energy and momentum or kinetic energy. Putting

$$p_1 - p_2 = \Delta p = Total\ pressure drop$$

$$\frac{1}{2}(\rho_2 v_2^2 - \rho_1 v_1^2) = \Delta p_m = momentum\ \ gain\ \ pressure\ \ drop.$$

$$g(\rho_2 z_2 - \rho_1 z_1) = \Delta p_z = potential\ energy\ gain\ pressure drop.$$

$$\therefore \Delta p = \Delta p_m + \Delta p_z$$

III. Pressure drop concept for single phase viscous flow through a pipe or tube

Considering viscous flow through a pipe of flow area A & wetted perimeter C, the equivalent momentum balance equation can be written as

$$\left[p - \left(p + \frac{\partial p}{\partial x}dx\right)\right]A - \rho g A dx\cos\theta - \tau C dx = \rho A dx \times a_x$$

Where ɵ = inclination of flow path with vertical.

Dividing by A dx

$$-\frac{\partial p}{\partial x} - \rho g\cos\theta - \tau\frac{c}{A} = \rho a_x$$

Putting $a_x = v\frac{\partial v}{\partial x}, \quad \cos\theta = \frac{\partial z}{\partial x}$

$$\therefore -\frac{\partial p}{\partial x} - \rho g \frac{\partial z}{\partial x} - \tau \frac{c}{A} = \rho v \frac{\partial v}{\partial x}$$

$$\Rightarrow \partial p + \rho g \partial z + \tau \frac{c}{A} \partial x + \rho v \partial v = 0$$

$$\Rightarrow \partial p + \rho v \partial v + \rho g \partial z + \tau \frac{c}{A} \partial x = 0$$

Putting wall shear stress in terms Darcy friction factor

$$\tau = f \frac{\rho v^2}{2}$$

$$\therefore \partial p + \rho v \partial v + \rho g \partial z + \frac{f \rho v^2}{2} \times \frac{c}{A} dx = 0 ------------(5)$$

This represents the total momentum balance equation for single phase viscous flow.
Integrating the above equation we will find corresponding energy balance equation for incompressible viscous flow over the control volume.

$$(p_2 - p_1) + \rho\left(\frac{v_2^2 - v_1^2}{2}\right) + \rho g (z_2 - z_1) + \frac{f \rho v^2}{2} \times \frac{c}{A} L = 0$$

$$Since \int dx = L = Length\ of\ flow.$$

$$\therefore (p_2 - p_1) + \rho\left(\frac{v_2^2 - v_1^2}{2}\right) + \rho g (z_2 - z_1) + \frac{f \rho L v^2}{2} \times \frac{c}{A} = 0$$

For flow through a pipe putting $\frac{c}{A} = \frac{\pi d}{\frac{\pi}{4} d^2} = \frac{4}{d}$

$$\therefore (p_1 - p_2) = \rho\left(\frac{v_2^2 - v_1^2}{2}\right) + \rho g (z_2 - z_1) + \frac{4 f \rho L v^2}{2d} --------------(6)$$

This shows that the total pressure drop is shared as one part to cause the acceleration or momentum gain, another part to over come gravitation and the remaining part to overcome the fluid friction.

Let $(p_1 - p_2) = \Delta p$, $\rho\left(\frac{v_2^2 - v_1^2}{2}\right) = \Delta p_m$ $\rho g (z_2 - z_1) = \Delta p_z$

$$\frac{4 f \rho L v^2}{2d} = \Delta p_f = Frictional\ pressure drop.$$

$$\Delta P = \Delta P_m + \Delta P_z + \Delta P_f --------------------------------------(7)$$

For single phase incompressible flow through horizontal pipe

$$\Delta p_z = 0.$$

$$However\ \ for\ \ compressible\ \ flow\ \ \Delta P_Z = g(\rho_2 z_2 - \rho_1 z_1).$$

This is not zero, but neglected for actual design calculations.
Again the frictional pressure drop, which seems to be velocity dependant in the first sight, but a deep analysis of Darcy equation verifies the independency of velocity.

$$\Delta P_f = \frac{4 f L \rho v^2}{2d} = \frac{4L}{d} \times \frac{f}{2} \rho v^2$$

$$But\ \frac{f}{2} \rho v^2 = \tau$$

So, $\Delta P_f = \frac{4 \tau L}{d}$, in which τ is function of fluid property μ and is independent of velocity variation *in the flow direction*. Further momentum pressure drop, caused by momentum or velocity gain in the direction of flow may consider three separate cases.
Case-1

When the fluid is incompressible and flows through a pipe or tube of uniform cross-section, so that there will be no momentum gain and $\Delta P_m = 0$.

Case-2

When the fluid is incompressible and flows through a pipe or tube of decreasing cross-section, so that there will be some propersonate momentum gain and $\Delta P_m > 0$

Case-3

When the fluid is compressible and flows through a pipe or tube of uniform cross-section with same mass flow rate but decreasing density, that causes the increase of flow velocity and hence momentum gain. So $\Delta P_m > 0$. This is not the case of single phase flow, rather a typical case of flow with phase change as explained in subsequent article.

IV. Phase change pressure drop analysis.

When fluid changes phase from liquid to vapor say, during its flow, the pressure drop analysis requires rigorous theory, than the single phase flow. Here the pressure drop energy may not be the only source to maintain the flow on overcoming fluid friction, momentum gain and potential energy gain along with the contribution to the phase change energy. Generally the phase change energy is supplied either from some external source as heat or collected from the internal stored energy of the fluid, if the flow is adiabatic as in the case of flow through a capillary tube of a refrigerator. Here the moment or acceleration gain for flow through the uniform cross-sectioned pipe or tube is due to the phase change, for which energy is supplied from external or internal source, but not from pressure drop. This extra energy creates the boosting force through phase change for acceleration gain.

Since the internal boosting force is a +ve generation type, so the momentum equation can be modified as

$$-\frac{\partial P}{\partial x} - \rho g \frac{\partial z}{\partial x} - \tau \frac{C}{A} - F_g = \rho v \frac{dv}{dx}$$

$$\partial P + \rho v \partial v + \tau \frac{C}{A} \partial x + \rho g \partial z - F_g \partial x = 0$$

Where $F_g =$ boosting force per unit volume.

Now the energy equation can be found by integration of above momentum equation.

So, $P + \rho \frac{v^2}{2} + \frac{\tau C x}{A} + \rho g z - F_g x =$ constant.

$$\Rightarrow (P_1 - P_2) + F_g (x_2 - x_1) = \frac{1}{2}\left(\rho_2 v_2^2 - \rho_1 v_1^2\right) + \tau\left(\frac{C}{A}\right)(x_2 - x_1) + g(\rho_2 z_2 - \rho_1 z_1)$$

$$\Rightarrow \Delta P + F_g l = \frac{1}{2}\left(\rho_2 v_2^2 - \rho_1 v_1^2\right) + \tau\left(\frac{C}{A}\right) l + g(\rho_2 z_2 - \rho_1 z_1) ---------- (8)$$

$\because x_2 - x_1 = l$

Again here $F_g l$ represents the internal energy release $(u_1 - u_2)$ which along with pressure drop energy is utilized in the gain of momentum or kinetic energy, potential energy and overcome the friction. In actual practice as liquid refrigerant from condenser at high pressure and saturation temperature flows through the capillary tube that causes gradual pressure and corresponding saturation temperature drop, which also causes the corresponding internal energy release. Now this released internal energy is utilized in flash vaporization, increase of specific volume, flow velocity and momentum gain. Here the decrease of pressure compensates the increase of specific volume keeping nearly the product pv =constant in the enthalpy relation. Again the capillary tube is of uniform bore, so pressure drop energy has no contribution towards momentum gain rather to overcome the friction and potential energy gain.

Without the aid of internal energy boosting the pressure drop relation introduces some controversy with the experimental results the property table. To understand this controversy if we ignore the internal energy boosting, the actual pressure drop should be shared in the gain of momentum (momentum pressure drop share) and overcome the friction (frictional pressure drop share).

Mathematically $\Delta P = \Delta P_m + \Delta P_f$

Where $\Delta P_m = \frac{1}{2}(\rho_2 v_2^2 - \rho_1 v_1^2)$ & $\Delta P_f = \tau\left(\frac{C}{A}\right)L = \frac{4 f L \rho v^2}{2d}$

Here the discretized finite element analysis for flow of liquid refrigerant through the capillary can verify that the only pressure drop energy is not sufficient to overcome the friction and supply for momentum gain. The following calculated results in the tables using the experimental data from refrigerant property table becomeevident to verify the controversy.

V. Pressure drop analysis for flow of R-600a in the capillary tube

Here the saturated liquid refrigerant from condenser at 30^0c is allowed to flow through the capillary tube of 1mm diameter to expand to -20^0c with a part flash vaporization along the Fanno line as in fig-2. Here the total temperature drop from 30^0c to -20^0c is divided into elementary steps of 10^0c, such as, 3o^{o}c, 20^0c, 10^0c, 0^0c - 10^0c and -20^0c. During expansion various properties of refrigerant at different temperatures, elementary actual pressure drops between adjacent temperature nodes and the corresponding momentum pressure drop shares have been determined from usual relations and the respective values are found as in the following tables.

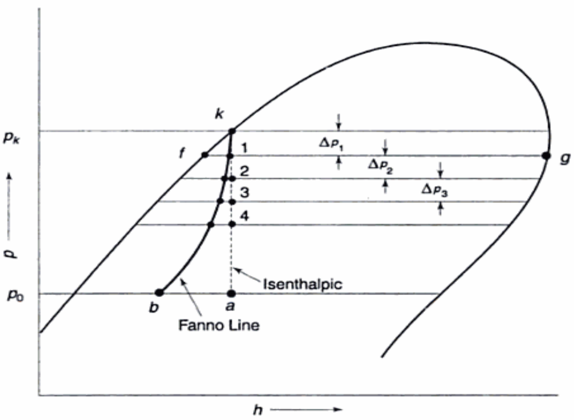

Fig-2,Ph Chart for Pressure & enthalpy changes along elementary lengths of the capillary in isenthalpic & Fanno line condition

Table -1. Different property values & velocity at different temperature nodes.

Temperature 0c	Fanno line enthalpy, h_i (kj/kg)	Dryness fraction (x_i)	Specific volume ($u_i \times 10^3 m^3 / kg$)	$u_i = G \times u_i$,(m/s)
30	272.370	0	1.826	2.935
20	272.225	0.0734	10.903	17.527
10	271.570	0.1388	25.117	40.376
0	269.475	0.1948	47.102	75.717
-10	264.175	0.2380	80.277	129.046
-20	252.240	0.2606	127.199	204.474

The above table is based on 0.1 tone refrigeration capacity and the corresponding mass flow rate of R-600a can be found to be 0.00126 kg/s determined from the following relation corresponding to the evaporator outlet enthalpy on vapor saturation line and inlet enthalpy on Fanno line.

$$m = \frac{Q_e}{h_g - h_i}$$

$$G = \left(4m/\pi d^2\right) = 1608 kg/m^2 s$$

Table-2. Calculation for elementary actual pressure drop and momentum pressure drop shares

Temperature ^0c	*Saturation pressure* P_i *bar*	ΔP_i *(bar)*	$u_i(m/s)$	Δu_i	$\Delta P_m = G \times \Delta u_i$
30	*4.080*		*2.935*		
20	*3.043*	*1.037*	*17.527*	*14.592*	*0.2346*
10	*2.220*	*0.823*	*40.376*	*22.849*	*0.3673*
0	*1.578*	*0.42*	*75.717*	*35.341*	*0.5681*
-10	*1.040*	*0.488*	*129.046*	*43.392*	*0.6965*
-20	*0.728*	*0.362*	*204.474*	*75.428*	*1.2125*

If ΔP_m is momentum gain pressure drop, then work done by this pressure drop = kinetic energy gain

$$\therefore \Delta P_m \times u_m = \frac{1}{2}Gu_2^2 - \frac{1}{2}Gu_1^2$$

$$\Delta p_m \times u_m = \frac{1}{2}G(u_2 + u_1)(u_2 - u_1) = Gu_m \Delta u$$

$$So,\ \Delta p_m = G\Delta u$$

Here the above tabulated result verifies after few nodes the momentum gain pressure drop, ΔP_m values exceed from the actual pressure drop values and confirms that the actual pressure drop must not be shared in frictional pressure drop and momentum gain pressure drop. Since in the equation (8) the term $F_g l$ represents internal energy change ($u_2 - u_1$) and with pressure drop energy the left two terms together represent the enthalpy drop. Again as the pressure is dropped during the adiabatic expansion of liquid refrigerant in capillary tube with simultaneous increase of specific volume, the product of pressure and specific volume almost remains constant. So the enthalpy change along the Fanno line $\Delta h = \Delta u + (p_2 v_2 - p_1 v_1) \cong \Delta u$. This verifies that enthalpy change is not affected by pressure drop, rather by internal energy drop. Here the change of pressure, specific volume and internal energy are very much inter related. The increase of specific volume is the cause of phase change through flash vaporization by utilizing the internal energy. First the viscous fluid friction causes the pressure drop and corresponding saturation temperature and internal energy drop. Now this internal energy drop is utilized in the increase of specific volume causing the gain of velocity, momentum and kinetic energy. So from this discussion the followings are obvious.

Internal energy drop = $\Delta u = F_g l = \frac{1}{2}(\rho_2 v_2^2 - \rho_1 v_1^2)$ = Momentum or kinetic energy gain.

Actual pressure drop (ΔP) = Frictional pressure drop (ΔP_f) + potential energy gain .

For small vertical distance flow , neglecting the potential energy gain, we have

Actual pressure drop (ΔP) = Frictional pressure drop (ΔP_f) = $\frac{4flv^2}{2d}$

So the actual total pressure should not be shared in momentum pressure drop, but can be used directly in the design of adiabatic capillary tube to determine its length and diameter for a given refrigeration capacity.

VI. CONCLUSION

The analysis of this paper summarizes into the following conclusions.

1-The paper high lights the existing concept of actual pressure drop for a fluid flow, which is shared as one part of frictional pressure drop, second part in the gain of potential energy and the third part in the gain of momentum

2-The adiabatic phase change of a fluid flowing through a uniform cross sectioned pipe utilizes its own enthalpy with simultaneous pressure, saturation temperature and specific volume drop.

3- In the pressure- volume product term of enthalpy, the decrease of pressure is almost compensated by the increase of specific volume keeping the product nearly constant.

4- The phase change is always effected by heat which is obviously collected from the internal energy. So the gain of momentum or kinetic energy through the specific volume change during the flow through a uniform cross sectioned pipe with phase change is nearly equal to the drop of internal energy.

5- Since neglecting the potential energy gain, the sum of pressure drop energy and internal energy is used to overcome the friction and in gain of momentum, so comparing, the total actual pressure drop is found to be used to overcome the friction.

This paper has the most important advantage to eliminate the condition of negative difference between the actual pressure drop and the momentum gain pressure drop for the determination of frictional pressure drop, which can be used in the design of adiabatic capillary tube of domestic refrigerators and similar other flow devices involving phase change.

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