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INVESTIGATION OF PRESSURE DROP ON UPWARD TWO-PHASE FLOW IN A VERTICAL ROD-BUNDLE

بحث فقد الضغط في سريان ثنائي الطور في حزمة قضبان رأسيه

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خلاصه : يتكون السريان ثنائي الطور في جميع الاجهزه الحراريه التي يسمح فيها بالغليان. السريان ثنائي الطور احادي الماده هو من الموضوعات المهمه في مجال الهندسة الحرارية والهندسة النووية. لتنفيذ التجارب المعملية اللازمه في هذا البحث تم تصميم وبناء دائرة اختبار تفي بهذا الغرض ويتكون جهاز الاختبار من حزمة ثلاث انابيب رأسيه مثلثية الشكل وموصلة كهربيا على التوازي. اقطار هذه الانابيب ١٠/١٢ مم وطولها ٢٠٠٠ مم يتدفق حولها المائع الى اعلى (ماء). ومن النتائج التي حصل عليها من التجارب العملية امكن التوصل الى ان فقدان الضغط الكلي في السريان ثنائي الطور وجد انه يزداد مع زيادة نسبة البخار بالاضافة الى ذلك وجد ان الاختلاف بين فقدان الضغط في التجارب العملية والنظرية يتراوح بين - ٢ الى + ٢٠ ٪.

ABSTRACT

Tow-phase flow is incorporated in all thermal equipments which involve flow boiling. Tow-phase single component flow is an extremely important system in the fields of thermal and nuclear engineering. To carry out the experimental study in this work a test rig has been constructed and built. The test section is a vertical 3 tube-bundle connected electrically in parallel. They are arranged in triangular shape. Each tube is 10/12 mm diameters and 200 cm in length. From the obtained experimental results, it is concluded that the total pressure drop in two-phase flow is found to increase with increasing void fraction (quality). In addition, it was found that the deviation between both experimental and theoretical pressure drop lies in the range from -2 to +20 %.

INTRODUCTION

Two-phase flow in the primary system of a pressurized water reactor is limited and may occur, as subcooled boiling with no net steam generation, only in some parts of the reactor core where the heat flux is very high. The situation is different in a boiling water reactor where the coolant circuit is dominated by twd-phase flow with considerable steam quality . Upward two-phase flow is also incorporated in some other reactors and many other steam raising facilities with vertical boiling channels. This includes the steam generators of pressurized water reactor systems . The boiling channels are usually in the form of rod bundles. Each rod bundle consists of parallel cylinders containing the nuclear fuel pins, arranged in a triangular or a square array and fixed to each other by spacers . If many studies are available on boiling in rod-bundles, little has been said about friction pressure drop or more generally the momentum balance in a rod bundle [1]. The total pressure drop between two points along a channel containing two-phase flow - without local restrictions - can be generally obtained by applying the momentum between the two points for steady state conditions, which yields [2,3] :

$$(dp/dz) = -[(1/A).\frac{\partial}{\partial z}(G^2 A/\rho) + \tau_w(P_w/A) + (g\rho \sin\theta)] \qquad (1)$$

Equation (1) can be expressed in the following form

$$(dp/dz) = -(\partial p/\partial z)_a - (\partial p/\partial z)_f - (\partial p/\partial z)_z \qquad (2)$$

where

(dp/dz) = total pressure gradient
$(\partial p/\partial z)_a$ = acceleration pressure gradient
$(\partial p/\partial z)_f$ = frictional pressure gradient
$(\partial p/\partial z)_z$ = gravitational pressure gradient

There are three main models applied to analyze the above terms in two-phase flow [2,3,4] :

1- the homogeneous flow model
2- the separated flow model and
3- the flow pattern models

From the above models, the homogeneous flow model is chosen for its simplicity.

In the homogeneous flow model the two-phase flow is assumed to be a single-phase flow having pseudo properties achieved by suitably weighting the properties of the individual phases. It is also assumed that there is no slip between the two phases and they are in thermal equilibrium. In this case, the homogeneous fluid density ρ_m is defined by the relation :

$$(1/\rho_m) = v_m = (x/\rho_v) + (1 - x)/\rho_l = [v_l + X v_{fg}] \qquad (3)$$

Substituting for ρ_m in Eq.1 considering channel with constant cross section , one gets

$$(\partial p/\partial z)_a = G^2(\partial v_m /\partial z)$$

Neglecting the compressibility of the liquid phase, one obtains

$$(\partial p/\partial z)_a = G^2 \left[(v_v - v_l).(\partial X/\partial z) + X\,(\partial v_v/\partial p)(dp/dz) \right] \tag{4}$$

Determination of the frictional pressure drop in two-phase flow is a problem that can hardly be solved on only a theoretical basis. Therefore, many empirical correlations based on experimental data are applied [3]. Even in turbulent single-phase flow, the friction factor is calculated from empirical relations by using Reynolds number and relative roughness as correlating factors. In general, the frictional two-phase pressure drop can be expressed in the following form:

$$[(\partial p/\partial z)_f]_{TP} = [\partial p/\partial z)_f]_{SP} \cdot \phi^2 \tag{5}$$

where ϕ^2 is a two-phase frictional multiplier. The two-phase friction multiplier can be expressed in several different formulas according to the assumptions made as reported in [2,3,5,6] . One of these relations is given by :

$$\phi^2 = [\,1 + X\,(v_{fg}/v_l)]\,[1 + X\,(\mu_{fg}/\mu_l)]^{-0.25} \tag{6}$$

In this case, the single-phase friction factor f_{SP} for liquid flow alone is obtained from the ordinary Blasius equation

$$f_{sp} = 0.316\,(\,G\,De/\mu_m\,)^{-0.25} \tag{7}$$

where μ_m is given by [2] :

$$(1/\mu_m) = [(X/\mu_v) + (1-X)/\mu_l\,] \tag{8}$$

The most widely used correlation for prediction of the two-phase frictional pressure drop is an empirical correlation that has been suggested by (Martinelli and Nelson) [2,3,5]. In this approach, a single-phase frictional pressure drop for the given geometry and the total mass flow rate is calculated and the multiplied by a two-phase multiplier , which is obtained from Martinelli-Nelson charts . This two-phase factor depends on steam quality and pressure. An extension to the Martinelli-Nelson approach has been suggested by Baroczy which takes into consideration the effect of the mass velocity [3] .
The gravitational pressure drop is also given by :

$$(\partial p/\partial z)_z = \rho_m\, g \sin\theta \tag{9}$$

An attempt has been made by Singal et al. [7] to develop a correlation for prediction of pressure drop during forced convective boiling of pure refrigerant 12 and other mixtures flowing horizontal tubes . It was found that the deviation between the measured and the predicted values (according to Martinelli-Nelson multiplier) lies within 30%.
In this work pressure drop in a convective boiling system is experimentally investigated. The boiling system simulates fuel elements in a boiling reactor or even a pressurized water reactor during a Loss Of Coolant Accident (LOCA).

EXPERIMENTAL TEST LOOP

Schematic layout of the experimental loop is shown in Fig.(1). This loop consists mainly of test section (4), water condenser (6), preheater (2) and pump (1).

The test section - which simulates a nuclear fuel element - consists of three stainless steel tubes. They are arranged in a triangular shape. The outside diameter of each tube is 12 mm and is 2.05 meter in length. The three tubes are housed in a stainless steel vertical tube with inside diameter of 63.5 mm. The total surface area of the three tubes is 2262 cm2.

The test section is heated electrically by direct current supplied from a welding rectifier unit. Distilled water enters to the test section through a one way valve. A mixture of saturated vapor and saturated water flows upward and leaves the test section to the water cooled condenser. The test section is equipped with U-tube mercury manometer and a pressure gauge to measure the inlet gauge pressure. The total pressure drop across the test section is measured by connecting the rubber hoses of a differential mercury manometer to the pressure tapes at the inlet and outlet of the test length (2.0 m). The total pressure drop is then calculated using the following relation:

$$\Delta p_t = \gamma_w \, (2.0 - h) + \gamma_m h$$

where γ_w = specific weight for water , $Kg/m^2.s^2$

γ_m = specific weight for mercury

h = manometer reading (height difference), m

Δp_t = total pressure drop along the test section, N/m2

EXPERIMENTAL RESULTS AND DISCUSSION

All experiments carried out in this work cover the following heat transfer regimes:

1-Single-phase forced convection. 2-Subcooled nucleate boiling.
3-Saturated nucleate boiling with low quality.

The experiments are carried out in the operating conditions which are allowed by the test facility. For each run, the total pressure drop for single- and two- phase flow through the test section is calculated and compared with the measured value. Calculation of the pressure drop in the two-phase length is performed according to the homogeneous model. The frictional pressure drop is predicted according to equations (5),(6),(7), and (8) . For this purpose a computer program has been proposed [8].

Generally, the obtained results of calculations show that the total pressure drop in the two-phase flow region becomes the predominant value as the boiling length increases. This is because the frictional part of the two-phase pressure drop increases rapidly as the void fraction increases, where the flow area is reduced by the presence of the steam. With higher heat flux, the single-phase pressure drop increases due to the change in the properties of the water, and the two-phase pressure drop also increase due to the increase of the void fraction for he same mass flow rate. The calculation procedure for a typical run is performed according to the homogeneous model. The Table below shows the results for four selected runs.

Run no.	1	3	8	26
W (Kg/hr)	500.00	700.00	700.00	650.00
G, (Kg/m2.s)	49.12	68.76	68.76	63.85
q" (W/cm2)	6.60	6.60	6.14	5.45
Exit quality X (%)	0.64	0.70	1.05	0.64
Boiling length z (m)	1.75	1.62	1.38	1.61
Single-phase pressure gradient N/m2/m				
$(\Delta P/\Delta z)_f$	2.10	3.50	3.00	3.10
$(\Delta P/\Delta z)_a$	0.03	0.04	0.04	0.03
$(\Delta P/\Delta z)_z$	9364.00	9327.00	9329.70	9325.00
Total $(\Delta P/\Delta z)_{SP}$	9366.10	9330.50	9332.70	9328.60
Two-phase pressure gradient N/m2/m				
$(\Delta p/\Delta z)_f$	4.90	8.50	12.30	8.20
$(\Delta P/\Delta z)_a$	65.00	81.50	79.00	74.10
$(\Delta P/\Delta z)_z$	2924.00	2962.00	2246.80	2856.40
Total $(\Delta P/\Delta z)_{TP}$	2993.90	3052.00	2338.10	2938.70
Total pressure drop ΔP (N/m^2)	16390.67	16275.17	14328.74	16165.14

An example of the calculated pressure drop is illustrated in Fig.(2). A comparison between the theoretical and experimental results is also shown in Fig. (3). It is clear from Fig.(3) that the deviation between the experimental and theoretical values lies within 20 % . This deviation may be due to the existence of some heterogeneities in the cross section of the test section which characterize the subchannels of the rod-bundle.

CONCLUSIONS

From the previous discussion, the following conclusions can be drawn:

i-The total pressure drop in the two-phase flow region increases with increasing void fraction (quality) because the frictional pressure gradient term increases rapidly for higher void fractions due to the reduction in the flow area.

ii-The frictional term in the two-phase flow region is found to be higher than the corresponding term in the single-phase flow region.

iii-The total pressure drop in two-phase flow region is nearly one third the total pressure drop in one-phase flow region for the considered run.

iv-It was found that the deviation between the experimental and theoretical pressure drop lies in the range from −2 to +20 %.

NOMENCLATURE

A	Area	(m^2)
G	Mass velocity.	$(Kg/m^2.s)$
q"	Heat flux.	(W/cm^2)
h	Height	(m)
f	Friction factor	
X	Exit quality.	(%)
z	Preheating length.	(m)
W	Mass flow rate.	(Kg/hr)
P	Perimeter	(m)
Δp	Pressure drop.	(N/m^2)
μ	Dynamic viscosity	$(N.s/m^2)$
v	Specific volume	(m^3/Kg)
ρ	Density	(Kg/m^3)
γ	specific weight	$(Kg/m^2.s^2)$
ϕ^2	Two-phase friction multiplier	
τ	Shear stress	(N/m^2)

Subscripts

a	Acceleration
l	Liquid
f	Friction
m	mean/mercury
v	Vapor
fg	Liquid-gas
SP	Single-phase
TP	Two-phase
t	Total
w	Wall/Water
z	Static head

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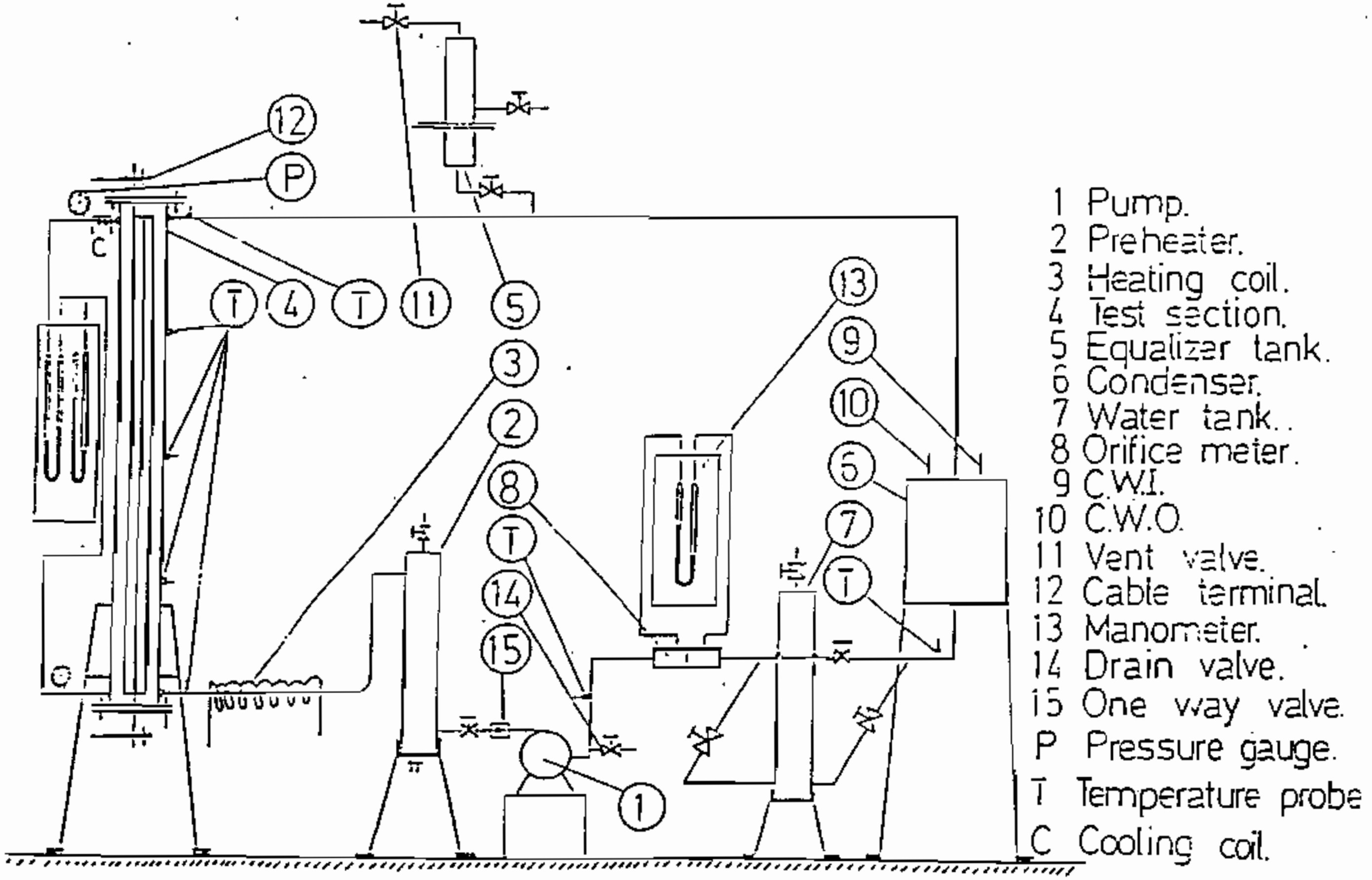

Fig.(1) Schematic layout of the experimental loop.

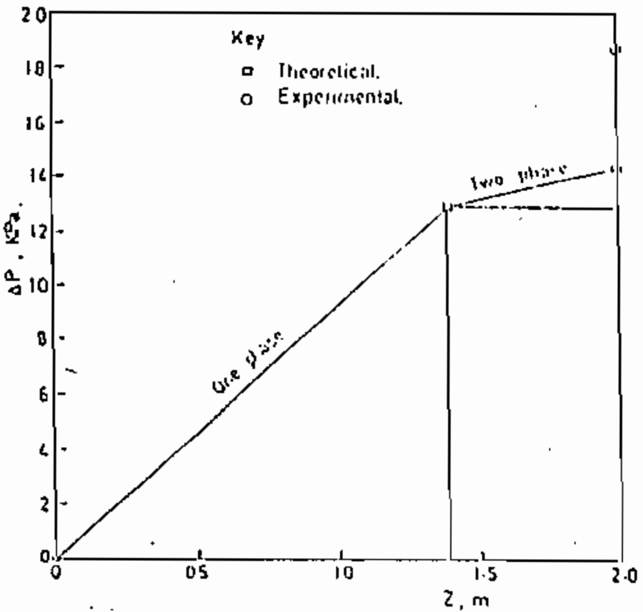

Fig.(2) Pressure drop distribution along the test section.

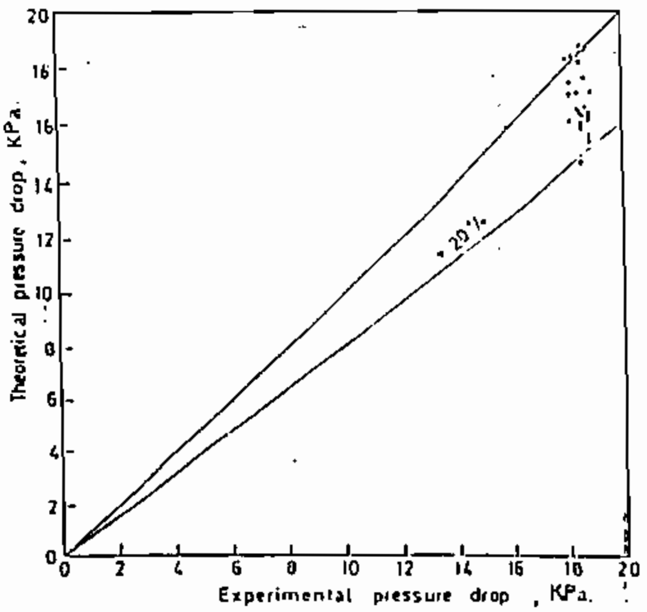

Fig.(3) Comparison between the experimental and theoretical pressure drop.