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DIFFUSING A HOMOGENIZED TWO-PHASE FLOW

I. OWEN, A. ABDUL-GHANI and A. M. AMINI
Heat and Mass Transfer Laboratory, Department of Mechanical Enginneering, University of Liverpool, P.O. Box 147, Liverpool L69 3BX, England

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Abstract—This paper describes the results of an experimental study in which the pressure recovery from a homogenized two-phase flow in a conical diffuser was measured. The flow was an air/water mixture with volumetric void fractions up to 35%. Although the pressure recovery was reduced because of the two-phase mixture, the use of a diffuser is still beneficial. For example, whereas a 7° diffuser operating in a single-phase flow achieves a pressure recovery of about 85%, the same diffuser operating in a flow with a 20% void fraction has a pressure recovery of about 70%; this compares with about 20% through a sudden expansion. It has been found that the optimum angle of the diffuser in two-phase flow is the same as that in single-phase flow, i.e. 7°. The pressure recovery coefficient has been defined using the homogeneous density and the velocity of the mixture at the inlet to the diffuser. An expression is proposed for predicting the pressure recovery coefficient of a diffuser operating in two-phase flow.

Key Words: pressure recovery, diffusers, two-phase flow

1. INTRODUCTION

The recovery of static pressure from a high-velocity flow is conventionally achieved in a carefully designed expanding section of ducting or pipework known as a diffuser. Diffusers can have plane walls to suit rectangular section ductwork or, for circular pipework, they can be conical. Typical applications are at the discharge outlets of pumps and fans, in the outlet section of a venturimeter, at the outlet of a jet pump, in air-conditioning and other ductwork where it is important to reduce the flow losses to a minimum. There have been many papers published on the topic of diffusers, but for a comprehensive review of the available data, the series of documents published by the Engineering Sciences Data Unit provide a valuable source of information.

Whilst diffusers have been carefully optimized and characterized for single-phase incompressible and compressible flows, relatively little work has been carried out into the performance of diffusers in two-phase, gas/liquid flows. In the present study, a conical diffuser with a 1:9 area ratio has been tested in two-phase air/water flows with volumetric void fractions up to 35%. The included angle of the diffuser was varied form 5° to 11° to determine the optimum angle, should one exist, and in addition the pressure recovery of a sudden expansion with the same area ratio was also measured. This latter exercise has enabled a comparison to be made beween some of the present data and that already published for two-phase pressure drops at sudden expansions with no phase-change.

Previous relevant research into pressure recovery from two-phase flows include that by Schneiter (1962) who, as part of a study into the performance of a jet pump operating on two-phase flow, measured the pressure recovery in a conical diffuser; Hench & Johnston (1972), in a study related to the flow of steam/water mixtures in water-cooled nuclear reators, measured the pressure recovery of a two-phase (air/water) flow in a rectangular two-dimensional diffuser. The present study covers a wider scope than that of Schneiter (1962), but where they coincide, the results are similar. The data of Hench & Johnston (1972) was restricted to two-dimensional diffusers with area ratios between 1.3 and 4 and the volume void fraction was varied between 30 and 75%. These conditions are significantly different to the present study and it is not possible, therefore, to directly compare the two. The low area ratio and the large expansion angles of the diffuser used by Hench & Johnston (1972) meant that much of the pressure recovery (up to about 50%) was occurring in the parallel duct downstream of the expansion and the overall pressure recoveries reported by them are much lower than those being reported herein.

Two-phase gas/liquid flows are often violent and difficult to pump, to control and to meter, and for these reasons it has always been good practice to avoid them. However, developments in the subsea oil industry aimed at increasing operating efficiencies are leading towards multiphase flow systems and in these circumstances reducing the pressure losses will be important.

2. PRESSURE RECOVERY IN SINGLE- AND TWO-PHASE FLOWS

When an incompressible flow is slowed from a velocity V_1 to V_2, there is a potential static pressure recovery

$$p_2 - p_1 = \tfrac{1}{2}\rho(V_1^2 - V_2^2), \tag{1}$$

where ρ is the density of the fluid. By measuring the actual pressure increase in a diffuser, and noting that the dynamic pressure at the exit will be small compared with that at the inlet, a pressure recovery coefficient, Ct, can be defined

$$\mathrm{Ct} = \frac{p_2 - p_1}{\frac{1}{2}\rho V_1^2}, \tag{2}$$

where V_1 is the velocity at the diffuser inlet.

In two-phase flow the mixture density may change as the gas-phase density increases with the pressure. The homogeneous density can be written in terms of the void fraction, ϵ, as

$$\rho_\mathrm{m} = \epsilon\rho_\mathrm{G} + (1-\epsilon)\rho_\mathrm{L}, \tag{3}$$

where the subscripts G and L refer to the gas and liquid phases respectively, and ϵ is related to the volume flow rates, Q, by

$$\epsilon = \frac{Q_\mathrm{G}}{Q_\mathrm{G} + Q_\mathrm{L}}; \tag{4}$$

this definition of void fraction is known as the volumetric void fraction.

In two-phase flows where the continuous phase is liquid, it is more appropriate to describe the gas fraction in terms of volume rather than mass, since it is easier to relate to the values quoted. However, for the sake of analysis it is easier to consider the mass fraction of the mixture, since this does not change with pressure as does the volume fraction (assuming there is no mass transfer between the phases). Therefore, the homogeneous mixture density can be expressed in terms of the mass fraction (quality, x), as

$$\frac{1}{\rho_\mathrm{m}} = \frac{x}{\rho_\mathrm{G}} + \frac{(1-x)}{\rho_\mathrm{L}}, \tag{5}$$

where x is related to the mass flow rates, $\dot{m}$, of the phases by

$$x = \frac{\dot{m}_\mathrm{G}}{\dot{m}_\mathrm{G} + \dot{m}_\mathrm{L}}. \tag{6}$$

For compressible flow, the pressure increase is related to the velocity change by the Euler equation:

$$\frac{\mathrm{d}p}{\rho} + V\,\mathrm{d}V = 0. \tag{7}$$

By assuming the gas phase acts as an ideal gas, the mixture density in [5] can be written as

$$\frac{1}{\rho_\mathrm{m}} = \frac{x\mathrm{R}T}{p} + \frac{(1-x)}{\rho_\mathrm{L}}. \tag{8}$$

Equation [7] can now be integrated to yield a compressible two-phase pressure recovery coefficient, Cct:

$$\mathrm{Cct} = \frac{x\mathrm{R}T\log_\mathrm{e}\left(\dfrac{p_2}{p_1}\right) + \dfrac{(1-x)}{\rho_\mathrm{L}}(p_2 - p_1)}{\frac{1}{2}(V_1^2 - V_2^2)}. \tag{9}$$

In two-phase flow the velocity at any section has strictly to take account of the slip between the two phases. In the present study there will be slip; however, an aim of the study is to present as simple an expression as possible for the two-phase flow pressure recovery. The mixture properties, therefore, have been defined on the basis of the mixture being homogeneous (uniform dispersion of phases and equal phase velocity). In this case the velocity at any section is calculated as the local total volume flow rate divided by the cross-section area.

Having adopted the concept of the homogeneous density it would be more consistent if a pressure recovery coefficient was defined in the usual way, as shown by [2]. Thus, a practical two-phase pressure recovery coefficient, Ct, would be:

$$\mathrm{Ct} = \frac{p_2 - p_1}{\frac{1}{2}\rho_m V_1^2}, \tag{10}$$

where ρ_m and V_1 are specified at the entry to the diffuser.

From the experimental data it will be possible to evaluate the two coefficients (Cct and Ct) and to compare their merits.

2.1. *Pressure recovery in a sudden expansion*

The worst case for recovering pressure from a high velocity flow is that of an abrupt expansion from area A_1 to A_2. This case has been studied by a number of investigators in relation to losses in two-phase flow piping systems (e.g. Lottes 1961; Chisholm & Sutherland 1969; Delhaye 1981; Wadle 1989). The sudden expansion has also been studied in the present work and the various results can therefore be compared. The pressure loss correlations of the different investigators have been cast into the form of Ct in [10].

An early formulation based on a momentum balance was presented by Lottes (1961) but attributed to Romie. The form of the equation recommended by Delhaye (1981) is

$$\mathrm{Ct} = 2\frac{A_1}{A_2}\rho_m\left(1 - \frac{A_1}{A_2}\right)\left[\frac{(1-x)^2}{(1-\epsilon)\rho_L} + \frac{x^2}{\epsilon\rho_G}\right]. \tag{11}$$

Lottes (1961) further simplified the momentum balance by assuming that all the pressure loss takes place in the liquid phase. Wadle (1989) adapted this approach by assuming the voidage remains constant through the expansion. For the void fraction Wadle recommends the use of a void correlation, ε, proposed by Rouhani (1969):

$$\mathrm{Ct} = 2\frac{A_1}{A_2}\rho_m\left(1 - \frac{A_1}{A_2}\right)\left[\frac{1}{\rho_L(1-\varepsilon)^2}\right], \tag{12}$$

where

$$\varepsilon = \frac{\dfrac{x}{\rho_G}}{\dfrac{1 + 0.12(1-x)}{\rho_m} + \dfrac{W_{rel}}{\dot{m}}}$$

and

$$W_{rel} = \frac{1.18}{\sqrt{\rho_L}}[\sigma g(\rho_L - \rho_G)]^{1/4};$$

σ is the surface tension.

Chisholm & Sutherland (1969) proposed the following model:

$$\mathrm{Ct} = 2\frac{A_1}{A_2}\frac{\rho_m}{\rho_L}\left(1 - \frac{A_1}{A_2}\right)(1-x)^2\left(1 + \frac{C}{X} + \frac{1}{X^2}\right), \tag{13}$$

where

$$C = \left[1 + \frac{1}{2}\left(\frac{\rho_L - \rho_G}{\rho_L}\right)^{1/2}\right]\left[\sqrt{\frac{\rho_G}{\rho_L}} + \sqrt{\frac{\rho_L}{\rho_G}}\right]$$

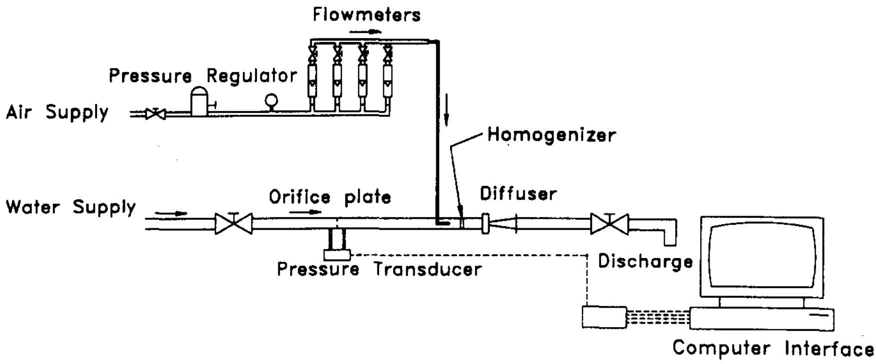

Figure 1. Schematic diagram of the diffuser test rig.

and

$$X = \left(\frac{1-x}{x}\right)\sqrt{\frac{\rho_L}{\rho_G}}.$$

Wadle (1989) discusses a number of publications concerned with two-phase through sudden expansions. He also recommended a formulation of his own, where

$$\mathrm{Ct} = K\rho_m\left[1-\left(\frac{A_1}{A_2}\right)^2\right]\left[\frac{x^2}{\rho_G}+\frac{(1-x)^2}{\rho_L}\right]. \qquad [14]$$

He determined the coefficient K to be 2/3; the significance of which will be discussed later in the present paper.

3. EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 shows the two-phase flow facility used to test the diffuser. The water supply provided from a large tank with a 35 m head, was metered by a calibrated orifice plate whose pressure differential was measured by a transducer and recorded by a microcomputer. One thousand readings were recorded and averaged to produce a reliable flow rate. Very low flow rates were measured by discharging the flow from the diffuser into a weightank. The air to the rig was provided by the laboratory main supply and was measured by high-pressure variable area flowmeters. To determine the volumetric void fraction at any position in the flow it was necessary to correct the air volume for the local pressure. The air and water were mixed about 2 m upstream of the diffuser and were homogenized by a perforated plate inserted about 0.5 m upstream of the diffuser. The diffuser was horizontal for all the tests.

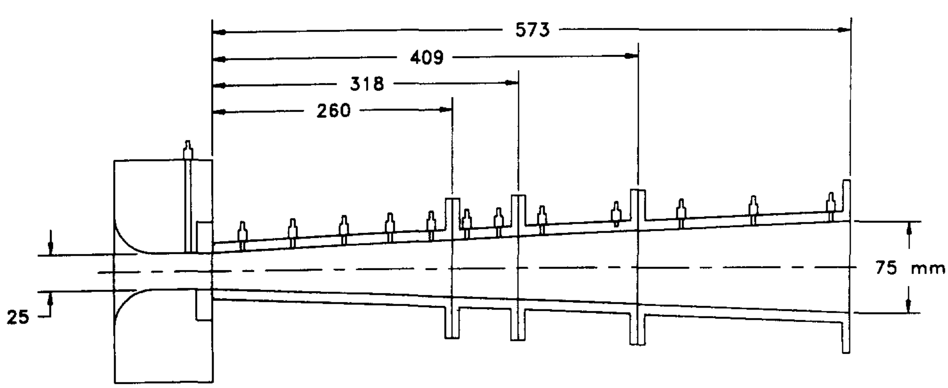

Figure 2. Diffuser and nozzle assembly.

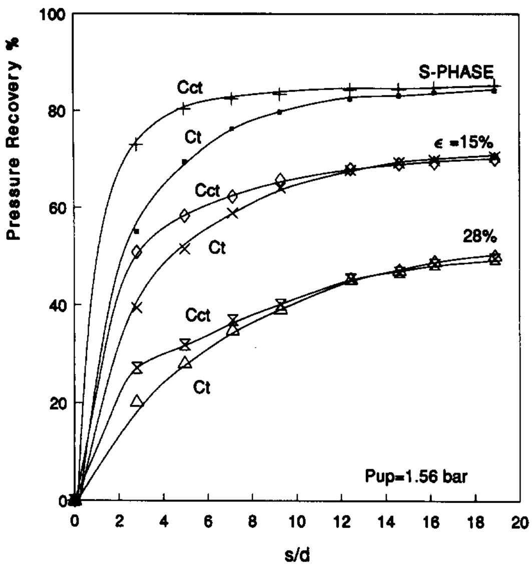

Figure 3. Comparison of pressure recovery for a 7° diffuser based on mixture density (Ct) and Euler (Cct).

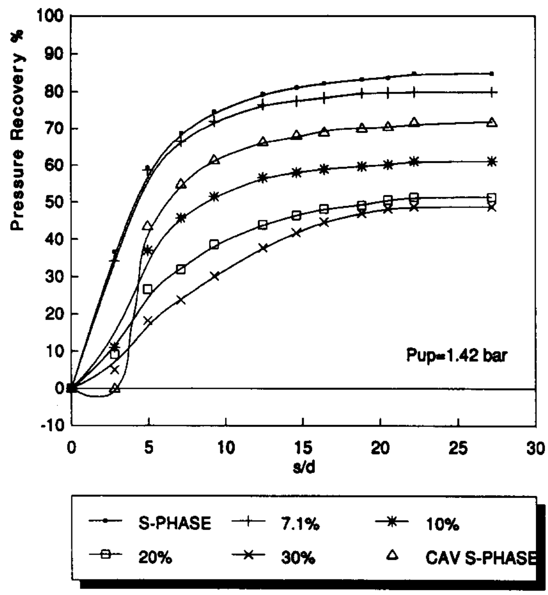

Figure 4. Pressure recovery for a 5° diffuser as a function of s/d in single-phase, cavitating single-phase and two-phase flows.

The flow was introduced to the diffuser via a parabolic nozzle manufactured in accordance with BS 1042 (1964). This arrangement meant that the inlet conditions to the diffuser were those at the throat of the nozzle. The rapid acceleration of the mixed flow into the nozzle will encourage slip between the liquid and gas phases. However, it also encourages the two phases to mix thoroughly and the volume flow definition of void fraction from [4] still holds: whether this definition is satisfactory or not will become more clear from the experimental data. The nozzle and the diffuser are shown in more detail in figure 2. Pressures in the nozzle and along the diffuser were measured by mercury manometers, whilst the pressures in the diffuser and the flow rate of water

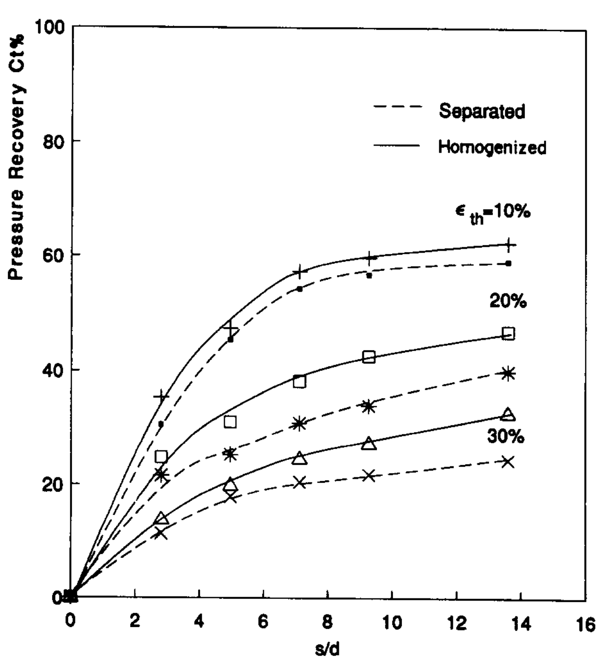

Figure 5. Comparison between pressure recovery for stratified and bubbly flow for an 11° diffuser.

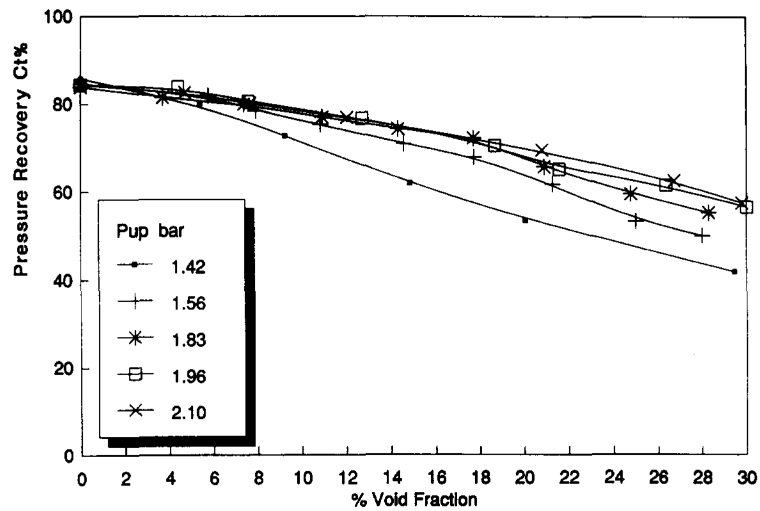

Figure 6. Variation of the overall pressure recovery (Ct) for a 7° diffuser with void fraction.

were controlled by the two values shown. The diffuser was originally manufactured with a 5° total angle and was then subsequently machined to form 7°, 9° and 11° angles, whilst maintaining the same overall area ratio of 1:9.

When varying the flow through the diffuser it was not possible to maintain all the remaining parameters constant. The procedure was to select an inlet pressure and, for a particular void fraction, to vary the flow rate. Therefore every time the water flow rate was changed, so too was the air flow to maintain the same void fraction. The experiments were carried out with upstream pressures between 1.42 and 2.11 bar (all pressures quoted are absolute) and void fractions (at the throat) up to 35%,

For higher flow rates, particularly in single-phase flow, cavitation was observed in the throat of the diffuser (i.e. in the nozzle) and whilst some measurements were made with the flow in this condition, the majority of the experiments were carried with no cavitation being present.

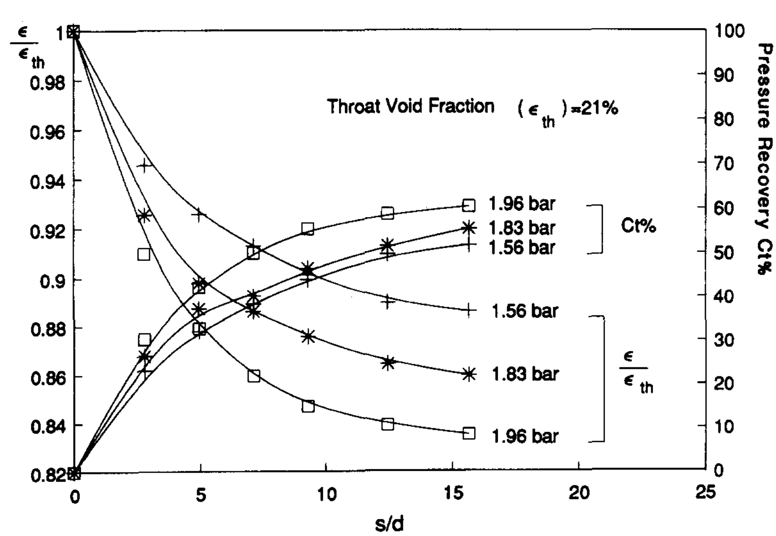

Figure 7. Variation of the void fraction through a 9° diffuser and its effect on the pressure recovery.

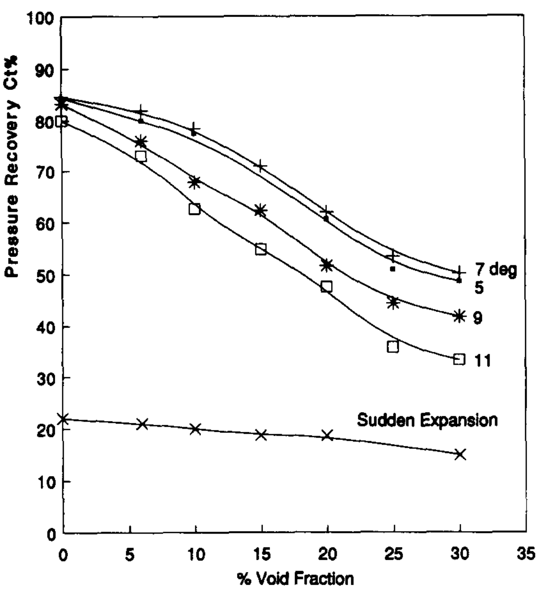

Figure 8. Effect of the diffuser angle on the pressure recovery for different void fractions and constant upstream pressure $P_{up} = 1.56$ bar.

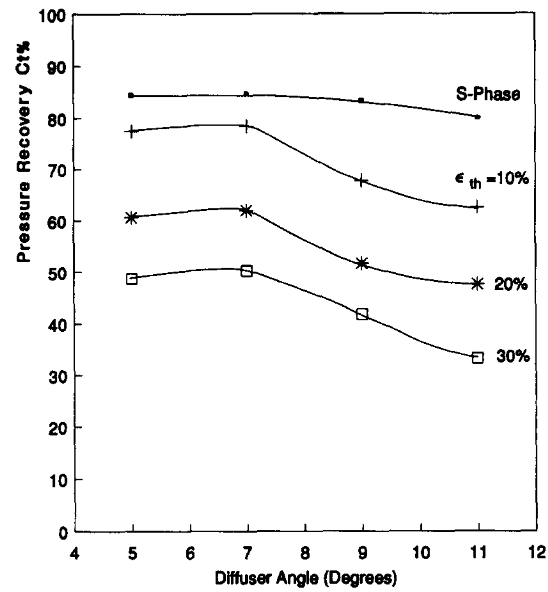

Figure 9. Effect of diffuser angle on the pressure recovery for constant void fraction and 1.56 bar upstream pressure.

4. RESULTS

The first question to be addressed is how to characterize the pressure recovery; i.e. which of Cct and Ct is the most suitable? Figure 3 shows the pressure recovery along the length, s, of the diffuser (d being the diameter of the diffuser inlet) in terms of both coefficients and it can be seen that it is only in the early stages of the process that the variable density and the local mixture velocity have an effect. In a diffuser it is overall pressure recovery that is important and at the end of the diffuser the two coefficients converge. The small difference between them is due to only one coefficient (Cct) taking account of the outlet velocity. For consistency with standard diffuser characteristics, therefore, the use of Ct is recommended. It should be noted that the conditions, i.e. the void fraction, density, velocity and initial pressure, relate to the throat of the diffuser. The pressures quoted for the different experiments, however, were measured upstream of the nozzle and are used only to distinguish between experiments.

A more complete set of data for the pressure recovery through the diffuser is shown in figure 4. It can be seen from the assymptotic form of the curves that all the recoverable dynamic pressure has been attained. The pressure recovery in two-phase flow is significantly lower than that in single-phase flow. Also shown in figure 4 are the effects of cavitation on the diffusion process. It can be seen that the minimum pressure in the cavitating flow is not at the throat but is just beyond it; this is due to the sudden voidage causing the liquid to accelerate, even though the passage area is expanding. The effect of cavitation on the pressure recovery is significant, causing a reduction from 85 to 71%. The overall effect of the two-phase flow (whether it be caused by cavitation or pre-mixed phases) is to reduce the pressure recovery. The reason for this is not difficult to understand when the flow is observed. Efficient pressure recovery depends on converting the kinetic energy of the flow into static pressure with as few fluid-dynamic losses as possible. The violent nature of the two-phase flow with extreme levels of turbulence is such that losses are inevitable. At higher void fractions and lower flow rates it was also observed that the flow separated from the wall, thus leading to further losses. An extreme example of this was where the flow became stratified in the diffuser. This effect is illustrated in figure 5, where it is shown how the separation of the phases reduced the pressure recovery below that obtained with the mixed two-phase flow. The two flow regimes could be obtained for the same void fraction by changing the flow rates.

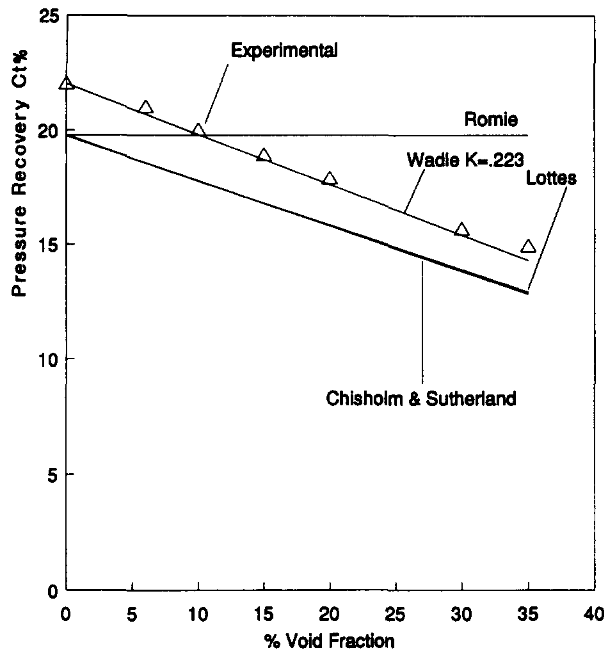

Figure 10. Two-phase pressure recovery for sudden expansion.

Figure 6 shows how the overall pressure recovery changes with void fraction and for different upstream pressure (P_{up}, measured before the nozzle). There is an effect due to the pressure, and this increases as the void fraction increase. It has not been possible in the present study to evaluate this effect properly, because it is not due simply to the local pressure but it is also due to the pressure drop, and hence flow rate, through the diffuser. The reason for the reduced pressure recovery is illustrated in figure 7 with reference to three different inlet pressures. It is already clear that the presence of the gas phase severely disrupts the diffusion process and the greater the proportion of gas, the greater the disruption. By considering the two sets of curves in figure 7 it is seen that the more the gas phase is recompressed (i.e. the void fraction is reduced), then the higher the pressure recovery. Thus, returning to figure 6, at the higher inlet pressures there will be higher flow rates and therefore greater pressure increases between the throat and the outlet. Since the void fraction is specified at the throat there will be a greater reduction in the void fraction for the higher inlet

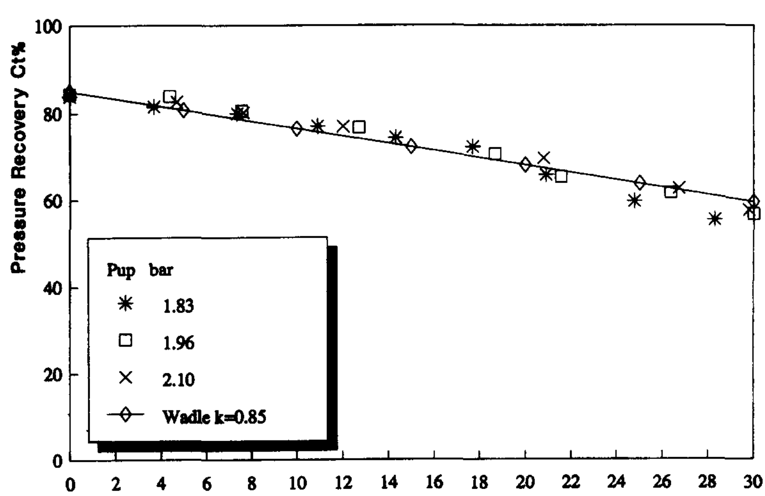

Figure 11. Variation of the overall pressure recovery (Ct) for a 7° diffuser with void fraction compared with Wadle's (1989) model.

pressures, as shown in figure 7. Whilst it is possible to explain the reduction in the pressure recovery observed at the lower inlet pressures, it has not been possible to quantify it. However, it can be seen that the difference in the pressure recovery at the higher inlet pressures (and hence flow rates) is not so great and since diffusers are normally used with high velocity flows it is believed that the data presented at these higher pressures is representative of typical working conditions.

Schneiter (1962) has also presented data for the pressure recovery in a 7° conical diffuser. The fluids used were air and water with void fractions up to 20%; throat pressures were between 2 and 4 bar. The pressure recovery was defined in a similar way to that shown in [10], but using the liquid rather than the mixture density. The diffuser pressure recovery presented by Schneiter (1962) for different void fractions is consistent with the present results and the effect of throat pressure, although not as noticeable as in the present study, was observed.

In figure 8 the pressure recovery for each diffuser angle is shown as a function of void fraction. Also shown is the pressure recovery from the sudden expansion. It is clearly seen that although the diffuser is less effective in two-phase flow, it is still beneficial compared with the sudden expansion. In figure 9 the pressure recovery is presented as a function of the diffuser angle for different void fractions. Diffusers are normally designed with angles of divergence of 7° and the single-phase characteristic confirms this optimum. It is clear, however, that this angle is also optimum for two phase flow and, in fact, the optimum is more pronounced.

5. DISCUSSION

A diffuser is capable of recovering the static pressure from a two-phase flow. A suitable parameter for describing the pressure recovery is Ct, where

$$\mathrm{Ct} = \frac{p_2 - p_1}{\frac{1}{2}\rho_m V_1^2};$$

ρ_m is the homogeneous mixture density at the inlet to the diffuser and V_1 is the inlet mixture velocity.

The optimum angle of the diffuser is shown to be 7°, the same as for single-phase flow, but the efficiency reduces as the void fraction is increased. In single-phase flow it is possible to quote a pressure recovery coefficient for a particular design of diffuser which will hold over a wide range of conditions. In two-phase flow it is necessary to quote an expression which takes account of the void fraction on the pressure recovery coefficient. To arrive at such an expression, use can be made of the formulations proposed for the sudden expansion in [11]–[14]. These expressions are shown in figure 10, together with the experimental data from the present study. The expression due to Romie, presented in [11], shows the pressure recovery to be independent of the void fraction. This was recognized by Wadle (1989) who presented this expression as a function of geometry only. The expressions due to Lottes (1961) and to Chisholm & Sutherland (1969) are extremely close and follow the trend of the present data but underpredict is consistently.

In his formulation, Wadle (1989) uses a factor, K, which he derived experimentally, The value he proposed was 2/3. This is inconsistent with the present study and, indeed, with what would be expected. Consider [14] with the void fraction equal to zero, so that the pressure recovery reduces to

$$\mathrm{Ct} = K\left[1 - \left(\frac{A_1}{A_2}\right)^2\right]. \qquad [15]$$

K is now the pressure recovery coefficient for a simple sudden expansion in single-phase flow. The value of this coefficient for an area ratio expansion of 1:9 is typically about 0.2 (e.g. Miller 1978). The value obtained in the present study is about 0.22, whilst that predicted by Lottes (1961) and Chisholm & Sutherland (1969) is 0.19. If the value 0.22 is inserted into [14] then the expression fits the data quite well, as shown in figure 10. If, for the case of the diffuser, the value of the single-phase pressure recovery coefficient, i.e. 0.85, is inserted into [14], then the resulting expression predicts the diffuser pressure recovery with reasonable accuracy (at least for the higher flow rates which, as stated earlier, is believed to be representative of realistic conditions). This result is shown in figure 11.

6. CONCLUSIONS

The study reported in this paper considered the expansion of single-phase, cavitating the two-phase (air/water) flows through conical diffusers and through a sudden expansion. The main conclusions can be drawn together as follows:

1. A conical diffuser is effective in recovering the static pressure from a high-velocity two-phase flow but this effectiveness is reduced as the void fraction increases.
2. The optimum angle of the diffuser is 7°.
3. The diffuser pressure recovery can be presented by

$$\mathrm{Ct} = \frac{p_2 - p_1}{\frac{1}{2}\rho_m V_1^2} = 0.85\rho_m\left[1 - \left(\frac{A_1}{A_2}\right)^2\right]\left[\frac{x^2}{\rho_G} + \frac{(1-x)^2}{\rho_L}\right].$$

4. The pressure recovery measured in a sudden expansion is reasonably consistent with the formulations proposed by Lottes (1961) and Chisholm & Shepherd (1969).

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