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AN ANALYSIS OF THE INTERACTION BETWEEN A SUBMERGED JET AND A RECEIVER-DIFFUSER IN A REVERSE-FLOW DIVERTER

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An Analysis of the Interaction Between a Submerged Jet and a Receiver-Diffuser in a Reverse Flow Diverter*

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ABSTRACT

Two mathematical models of the interaction between a submerged jet emanating from the nozzle of a reverse flow diverter (RFD) and a receiver-diffuser of a venturi-like reverse flow diverter are presented and compared with experimental data. Both models predict the output characteristics fairly accurately, although the experimentally measured flow is observed to saturate at higher values of jet dynamic pressure and at lower values of output load impedances. An analysis based on the inviscid flow model indicates cavitation as the likely cause of the flow saturation.

NOMENCLATURE

Variables

A	area
C_d	discharge coefficient
C_p	pressure recovery coefficient
K_d	diffuser loss coefficient
P	pressure
Q	volumetric flow rate
V	velocity
ρ	density

Subscripts

i	induced flow
j	jet flow

Subscripts (cont.)

n	nozzle outlet
o	output of diffuser
r	receiver inlet
s	supply or source
1	region between nozzle and receiver
2	entrance section of receiver
3	receiver exit and diffuser inlet

Superscripts

–	bar atop variable indicates normalized quantity

INTRODUCTION

The reverse flow diverter (RFD) has been shown to be an extremely useful device in fluid control and fluid power systems. The RFD is a generic name for a three-port device, as shown in Fig. 1(a), with a forward flow mode of fluid flowing from port 1 to port S, whereas in the reverse flow mode the fluid is diverted to port O. One type of RFD is the axisymmetric venturi-like RFD, shown schematically in Fig. 1(b), which has proven useful in displacement pumping systems [1–7] with an air piston and associated chambers. These pumping systems have reportedly [1–6] been used extensively in the British nuclear fuel reprocessing facilities, and it is anticipated that these pumping systems will prove to be extremely useful in harsh chemical process environments where ultrareliable leak-free operation is required.

In the venturi-like RFD, the conversion of static to dynamic pressure in the nozzle diverts the reverse flow to the receiver while the receiver-diffuser of the RFD recovers a portion of the original static pressure. In the forward flow mode, the fluid does not flow appreciably to port O because of a sufficiently large output impedance.

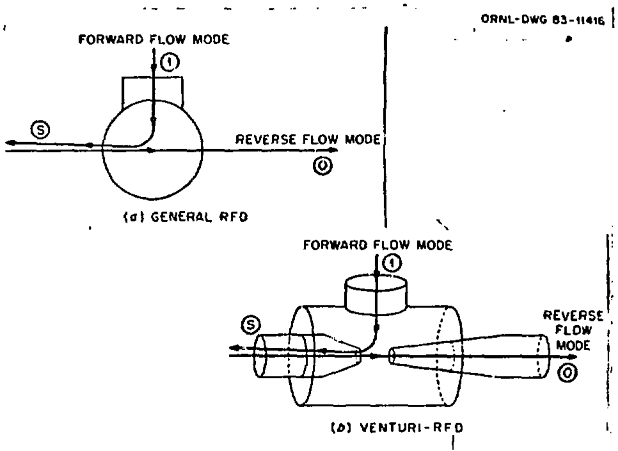

Fig. 1. Schematic of reverse flow diverter.

The primary purpose of this paper is to present two mathematical models for the venturi-like RFD in the reverse flow mode. It is the interaction of the submerged jet with the receiver-diffuser which is, by far, the most challenging portion of the device to accurately model.

THEORY

The mathematical models of the venturi-like RFD, to be developed in this section, are based on the assumptions of axisymmetric, steady and incompressible flow. The exit diameter of the nozzle of the RFD is assumed to be equal to the inlet diameter of the receiver-diffuser portion of the RFD.

Nozzle Model

The flow through the nozzle of the RFD is easily modeled by writing Bernoulli's equation between the inlet and the throat of the nozzle as

$$P_s = P_1 + \tfrac{1}{2}\rho V_{j1}^2 \ . \tag{1}$$

Noting that the volumetric flow rate through the nozzle of the RFD is equal to the product of the throat area and velocity, an expression for the flow rate of the jet emanating from the nozzle may be written as

$$Q_j = C_d A_n \sqrt{2(P_s - P_1)/\rho} \ , \tag{2}$$

where a discharge coefficient has been introduced to account for losses in the flow.

Source Flow Model of Receiver-Diffuser

One technique to model the interaction between a submerged jet and a receiver-diffuser is to consider the submerged jet impinging on the

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inlet to the receiver as a "source" or "driving" pressure equal to the sum of the static and dynamic pressures of the jet [7]. The difference between the source (total) pressure at the receiver entrance and the total pressure at the diffuser outlet is a result of *irreversible* losses occurring in the diffuser. Mathematically this may be expressed as

$$P_s - (P_o + \tfrac{1}{2}\rho Q_o^2/A_o^2) = K_d \tfrac{1}{2}\rho Q_o^2/A_r^2 \ , \tag{3}$$

where K_d is a diffuser loss coefficient, which is typically based on the maximum velocity occurring in the diffuser.

The pressure recovery coefficient, defined as the fraction of the dynamic pressure at the inlet to a diffuser *which is converted* to static pressure at the exit of the diffuser, is related to the diffuser loss coefficient, defined as

$$K_d = 1 - (A_r/A_o)^2 - C_P \ . \tag{4}$$

Substituting this equation into Eq. (3) yields

$$P_s - P_o = (1 - C_P)\tfrac{1}{2}\rho Q_o^2/A_r^2 \ . \tag{5}$$

The source pressure of the submerged jet is noted to be equal to the total (supply) pressure at the inlet of the *nozzle minus* those losses which occur in the nozzle. Neglecting these losses as a first approximation indicates that the source pressure is equal to the supply pressure applied to the nozzle inlet (i.e., C_d is equal to one). The validity of this approximation will be demonstrated in the Experimental System and Results Section.

Equation (5) may be written in a dimensionless form by dividing by Eq. (2) and rearranging algebraically, which yields

$$\frac{P_o - P_1}{P_s - P_1} = 1 - (1 - C_p)\frac{Q_o^2}{Q_j^2} \tag{6}$$

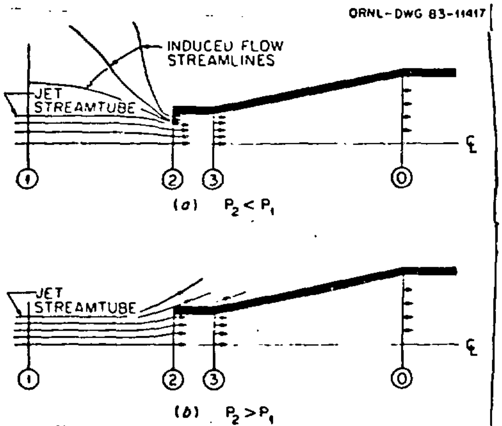
or

$$\bar{P}_o - \bar{P}_1 = 1 - (1 - C_p)\,\bar{Q}_o^2 \ . \tag{7}$$

Pressures are normalized with respect to the static pressure drop across the nozzle of the RFD, which from Eq. (1) is equal to the dynamic pressure of the jet; flows are normalized with respect to the flow emanating from the nozzle; and areas are normalized with respect to the nozzle exit and receiver inlet area.

Inviscid Jet Model of Receiver-Diffuser

A different mathematical model for the interaction between the submerged jet and the receiver-diffuser may be obtained by treating the submerged jet as inviscid. The behavior of the jet in the immediate vicinity of the receiver inlet is determined by the static pressure immediately inside the receiver inlet (Fig. 2). Referring to Fig. 2(a), if the static pressure immediately inside the receiver inlet (P_2) is less than the submerged jet static pressure (P_1), the jet streamtube experiences a reduction in area as a result of acceleration of the *fluid jet streamlines in the vicinity of* the receiver inlet. Because of this reduction in pressure, some ambient fluid is "induced" into the receiver inlet. A nonuniform velocity profile therefore exists at the receiver inlet. Both the jet flow and the induced flow are mixed in the receiver portion of the RFD and possess a uniform profile at the entrance to the diffuser (Sect. 3, Fig. 2).



(a) $P_2 < P_1$

(b) $P_2 > P_1$

Fig. 2. Inviscid jet and receiver-diffuser interaction.

If the pressure at the receiver inlet is greater than the ambient pressure (i.e., $P_2 > P_1$), the jet streamtube increases in area as indicated in Fig. 2(b). Therefore only a portion of the submerged jet is "captured" by the receiver. This flow is assumed to have a uniform velocity profile and is unchanged between Sects. 2 and 3 (Fig. 2).

Writing Bernoulli's equation between Sects. 1 and 2 (Fig. 2) for the jet streamtube yields

$$P_1 + \tfrac{1}{2}\rho V_{j1}^2 = P_2 + \tfrac{1}{2}\rho V_{j2}^2 \ . \tag{8}$$

This equation may be rewritten as

$$\left(\frac{V_{j2}}{V_{j1}}\right)^2 = 1 + \frac{P_1 - P_2}{\tfrac{1}{2}\rho V_{j1}^2} \tag{9}$$

or

$$\bar{V}_{j2}^2 = 1 + \bar{P}_1 - \bar{P}_2 \ . \tag{10}$$

From continuity the area of the jet streamtube at the receiver inlet is

$$\frac{A_{j2}}{A_{j1}} = \frac{V_{j1}}{V_{j2}} \tag{11}$$

or

$$\bar{A}_{j2} = 1/\bar{V}_{j2} = [1 + \bar{P}_1 - \bar{P}_2]^{-1/2} \ , \tag{12}$$

since $A_{j1} = A_n = A_r$.

For the case where $P_2 < P_1$, the area of the receiver entrance through which induced fluid flows is

$$A_{i2} = A_r - A_{j2} \tag{13}$$

or

$$\bar{A}_{i2} = 1 - \bar{A}_{j2} \ . \tag{14}$$

The velocity of the induced fluid is given by

$$P_1 = P_2 + \tfrac{1}{2}\rho V_{i2}^2 \tag{15}$$

or

$$\left(\frac{V_{i2}}{V_{j1}}\right)^2 = \frac{P_1 - P_2}{\tfrac{1}{2}\rho V_{j1}^2} \ , \tag{16}$$

which may be written as

$$\bar{V}_{i2}^2 = \bar{P}_1 - \bar{P}_2 \ . \tag{17}$$

The total flow through the receiver-diffuser is

$$Q_o = Q_{j2} + Q_{i2} \tag{18}$$

or

$$\bar{Q}_o = 1 + \bar{Q}_{i2} \ . \tag{19}$$

From Eqs. (14) and (17), the induced flow is then given as

$$\bar{Q}_i = [1 - \bar{A}_{j2}]\sqrt{\bar{P}_1 - \bar{P}_2} \ . \tag{20}$$

Combining Eqs. (12), (19), and (20) yields an expression for the normalized output flow rate of the receiver-diffuser as

$$\bar{Q}_o = [1 - (1 + \bar{P}_1 - \bar{P}_2)^{-1/2}]\sqrt{\bar{P}_1 - \bar{P}_2 + 1} \ . \tag{21}$$

The pressure at Sect. 3 (Fig. 2) is obtained by writing the momentum equation between Sects. 2 and 3 (Fig. 2). By neglecting shear losses, the momentum equation may be written as

$$P_2 A_r - P_3 A_r = \rho\,[A_3 V_3^2 - A_{j2} V_{j2}^2 - A_{i2} V_{i2}^2] \ . \tag{22}$$

Normalizing Eq. (22) yields

$$\bar{P}_2 - \bar{P}_3 = 2[\bar{V}_3^2 - \bar{A}_{j2}\bar{V}_{j2}^2 - \bar{A}_{i2}\bar{V}_{i2}^2] \ . \tag{23}$$

Substituting Eqs. (10), (12), (14), and (17) into Eq. (23), rearranging, and noting that $\bar{Q}_o = \bar{V}_3$, yields

$$\bar{P}_3 - \bar{P}_1 = \bar{P}_1 - \bar{P}_2 + 2(1 + \bar{P}_1 - \bar{P}_2)^{-1/2} - 2\bar{Q}_o^{\,2} \ . \tag{24}$$

Relating the pressure at Sect. 3 (Fig. 2) to the output pressure is accomplished through the pressure recovery coefficient, defined as

$$C_p = \frac{P_o - P_3}{\tfrac{1}{2}\rho V_3^2} \tag{25}$$

or

$$\bar{P}_o - \bar{P}_1 = \bar{P}_3 - \bar{P}_1 + C_p\bar{Q}_o^{\,2} \ . \tag{26}$$

Substituting Eq. (24) into Eq. (26) yields

$$\bar{P}_o - \bar{P}_1 = \bar{P}_1 - \bar{P}_2 + 2(1 + \bar{P}_1 - \bar{P}_2)^{-1/2} - (2 - C_p)\bar{Q}_o^{\,2} \ . \tag{27}$$

Equations (21) and (27) are two equations in three unknowns ($P_o - P_1$, Q_o, and $P_1 - P_2$). Although the unknown $P_1 - P_2$ could conceivably be eliminated between these two equations, it is simpler and neater algebraically to leave the equations separate.

For the case where $P_2 > P_1$ the velocity at the receiver entrance is still given by Eq. (9). The output flow rate is then equal to the receiver inlet area times the velocity at that point, or in normalized form

$$\bar{Q}_o = \bar{V}_{j2} = \bar{V}_3 = (1 + \bar{P}_1 - \bar{P}_2)^{1/2} \ . \tag{28}$$

Since for $P_2 > P_1$ the static pressure at Sect. 2 (Fig. 2) is equal to the static pressure at Sect. 3 (Fig. 2), Eq. (26) becomes

$$\bar{P}_o - \bar{P}_1 = \bar{P}_2 - \bar{P}_1 + C_p\bar{Q}_o^{\,2} \ . \tag{29}$$

For this case, Eqs. (28) and (29) are two equations in three unknowns. Combining these two into one equation yields

$$\bar{P}_o - \bar{P}_1 = 1 - (1 - C_p)\bar{Q}_o^{\,2} \ . \tag{30}$$

It is interesting to note that the expression for $P_2 > P_1$ is identical to the expression developed for the source flow model [Eq. (7)]. This is not surprising since for $P_2 > P_1$ the receiver entrance in the inviscid jet model is subjected to a uniform static and dynamic pressure or as previously termed the "source" pressure.

EXPERIMENTAL SYSTEM AND RESULTS

The axisymmetric venturi-like RFD, shown schematically in Fig. 1(b), was machined out of plexiglas. The exit diameter of the nozzle and the inlet diameter of the receiver-diffuser were 0.94 cm, whereas the length of the diffuser section of the receiver-diffuser was 7.62 cm with a diffuser exit diameter of 1.50 cm. This duffuser design was chosen to allow for operation in the fully stable regime of the stability map presented by Fox and Kline[8].

Supply and output pressures were measured with pressure sensor/transmitters. Flow rates were computed from level changes in tanks associated with fluid movements, whereas water (at room temperature) was used as the operating fluid in all tests. The experimental system features an automatic data acquisition system controlled by a Bristol UCS 3000 Unit Processor Controller.

The operating characteristics of the RFD nozzle are presented in Fig. 3 as a plot of the nozzle flow rate vs the difference in pressure across the nozzle. Also presented in this figure is the theoretical prediction for the nozzle flow from Eq. (2) for a discharge coefficient of unity. This assumption is equivalent to assuming an inviscid or a reversible flow. The assumption of an inviscid flow in the nozzle was previously made in the development of the mathematical model for the receiver-diffuser [7]. As is evident from a comparison of the data with the inviscid theory in Fig. 3, the assumption is valid.

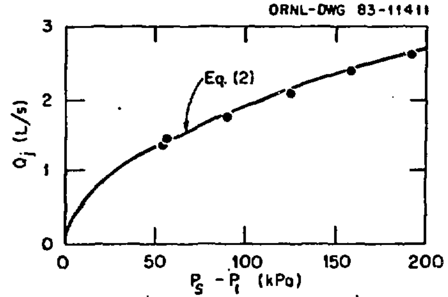


Fig. 3. Nozzle flow characteristics.

Figures 4, 5, and 6 present experimental flow characteristics of the receiver-diffuser for supply pressures of 73, 142, and 211 kPa respectively. Also presented on each figure are the predictions from the two mathematical models developed. The output characteristics of the receiver-diffuser are presented as a plot of the normalized output flow rate vs the normalized difference in static pressure across the receiver-diffuser.

Comparing the two model predictions first, it is observed (as earlier noted) that the two models yield identical results for large values of load impedances at the output of the receiver-diffuser. This corresponds to the case of the inviscid jet model having a pressure immediately inside the receiver entrance greater than the static pressure of the submerged jet

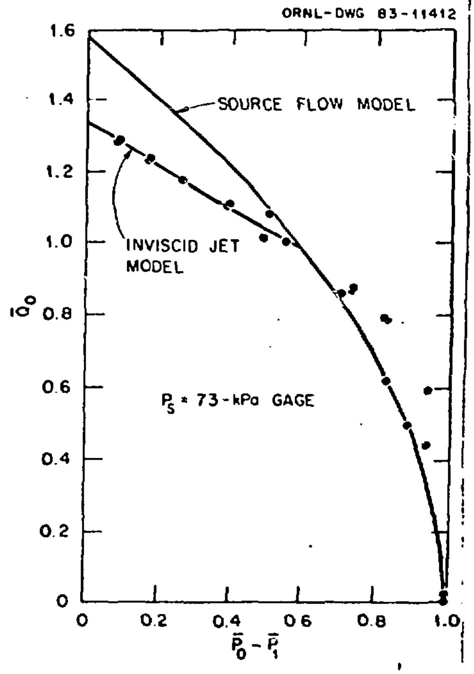


Fig. 4. Output characteristics for P_s = 73-kPa gage.

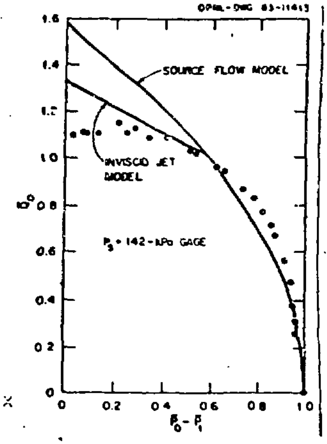


Fig. 5. Output characteristics for P_s = 142-kPa gage.

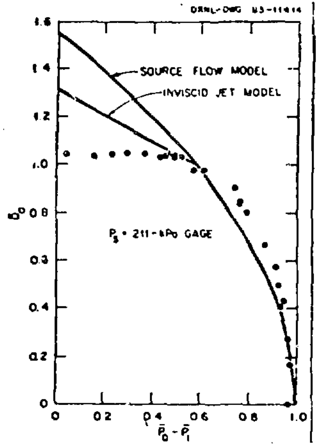


Fig. 6. Output characteristics for P_s = 211-kPa gage.

(i.e., the region where $\bar{Q}_o \leq 1$). As the load impedance is reduced, the output flow rate of the RFD increases and the two theories diverge for $\bar{Q}_o > 1$. The mathematical model based on a source or driving pressure at the receiver entrance predicts a higher output flow than the inviscid jet model as the load impedance is reduced (i.e., the output or back pressure is decreased).

Comparing the data to the two model predictions, it is observed that at higher load impedances (i.e., higher output pressures) reasonable agreement is noted between the two theories and data. As the load impedance is reduced, however, it is observed that the data for the lowest value of supply pressure (i.e., 73 kPa) continues in a continuous manner, whereas the experimental flow data for the two higher input pressures appear to saturate. The saturation for the highest supply pressure appears to occur before saturation for the middle supply pressure. For the lowest supply pressure (see Fig. 4), the inviscid jet model appears to predict more closely the performance of the receiver-diffuser than does the source pressure model.

Two possible reasons for the saturation of the output characteristics are noted. First, it has been observed [9] that the performance of a diffuser is highly dependent on the nature of the flow entering the diffuser. It is likely that the flow entering the receiver-diffuser has a secondary flow superimposed on it. This could, of course, cause premature separation of the flow in the diffuser. It is more likely, however, that cavitation of the fluid immediately inside the receiver-diffuser is occurring and this is the primary cause of the saturation of the data.

Some justification for this accusation of cavitation causing the data saturation (Figs. 5 and 6) may be obtained by further study of the inviscid jet model. Figure 7 presents the inviscid jet model predictions of the pressure immediately inside the receiver entrance in dimensional form plotted vs the dimensionless pressure difference across the receiver-diffuser for each supply pressure investigated. These predictions are for a submerged jet under an ambient pressure (i.e., P_1) of 117 kPa absolute which was the hydrostatic head impressed on the RFD during the experiments. For these conditions, it is observed that the inviscid jet model predicts negative absolute pressures as the load impedance is reduced, which is, of course, impossible. As the pressure decreases it eventually reaches a point where cavitation occurs. This cavitation pressure is determined primarily by the fluid temperature and dissolved gases in the fluid. The concurrence of cavitation leads to separation of the diffuser flow and saturation of the output flow. It is observed that the theory applied to the lowest supply pressure never predicts pressures below the saturation pressure of the fluid (~3.4 kPa absolute).

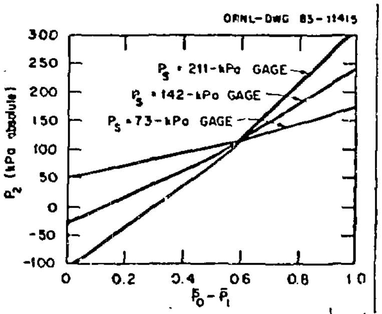


Fig. 7. Predicted receiver entrance pressure.

CONCLUSIONS

The mathematical models developed yield satisfactory agreement with the experimental behavior of a venturi-like RFD. The divergence between theory and data at higher supply pressures and lower values of load impedances is believed to be caused by cavitation occurring in the receiver-diffuser of the RFD.

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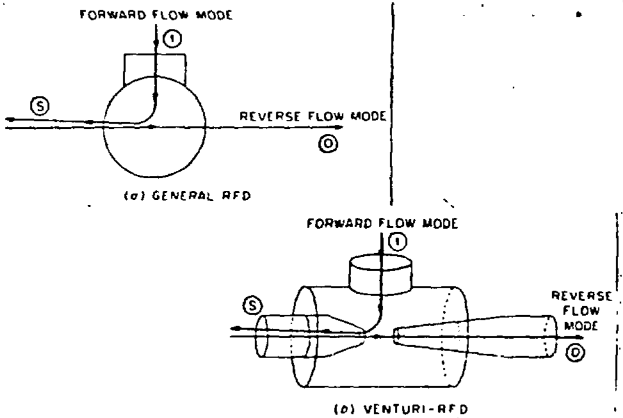

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