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Flow Control by Secondary Injection

R.K. DUGGINS
Professor of Mechanical Engineering, Faculty of Military Studies, The University of New South Wales,
Duntroon, A.C.T.

SUMMARY Firstly a review is given of previous work on secondary injection and of the existing knowledge of such a technique for controlling fluid flows either by energizing a boundary layer which would otherwise become unstable or by causing swirl to be imparted to the main flow.

Secondly, experimental investigations are described which employ these two types of secondary injection. The first investigation is aimed at assessing the merits of *axial* injection through an annular slot at the throat of a conical diffuser as a means of obtaining a high performance unit with short axial length. Preliminary results were published elsewhere which showed that injection yields a considerable improvement in the magnitude of the pressure recovery and the present results reveal a corresponding improvement in the quality of the discharging flow. The second investigation is concerned with vortex flow modulation in which flow control is achieved by means of *circumferential* injection. The results show that there is an optimum size of control port if the control power requirement is to be minimized for a given degree of modulation, but other aspects of the geometry have a surprisingly small effect on the control characteristics of the device. It is also found that, for both streamwise and circumferential injection, flow control depends largely on the *momentum* of the injected fluid.

1 INTRODUCTION

Situations often arise where it is desired to control the flow of a fluid without using a mechanical valve or some other device involving moving parts. A technique which gives such control is secondary injection whereby fluid from a secondary source is injected into the primary flow in a way which appropriately changes the flow pattern and results in a corresponding alteration of the primary flow-rate, either an increase or a decrease with complete shut-off being the limiting condition.

The two types of injection which are to be considered here are (i) injection into the boundary layer in an essentially streamwise direction and (ii) circumferential injection so as to impart a degree of swirl to the main flow or to increase the swirl already present. The applicability and effectiveness of the two types can be categorised by whether the primary flow is through a converging duct or a diverging one and here too both cases will be discussed. Results will be presented from two investigations which are proceeding under the author's supervision, one related to each of the above types of injection.

2 REVIEW OF PREVIOUS WORK

2.1 Streamwise Injection Through a Wall Slot

A number of reviews have been compiled on boundary layer energizing, notably by Jeromin (1970), and it is predicted from these that a single slot, located as far upstream as possible, is better than multiple slots for energizing purposes. Our particular concern is with injection through a single slot into diffusers and two previous investigations are worthy of mention, viz. by Nicoll and Ramaprian (1970) who used conical diffusers and by Fiedler and Gessner (1972) who used plane ones. In both cases the slot injection was in a direction tangential to the wall, and discharge from the diffuser was direct to the atmosphere. A suitable amount of injection was found to produce a considerable improvement in performance in both investigations.

For the sake of completeness, it is appropriate to mention that streamwise injection is not generally necessary in *favourable* pressure gradients such as in confined convergent flows since any tendency of the main flow to separate is considerably less than in divergent ones.

2.2 Circumferential Injection and Confined Swirling Flows

Investigations of confined swirling or vortex flows were comprehensively reviewed in 1971 by Lewellen and here it is necessary to mention only the more recent developments and the work which is directly related to the present topic of swirl addition for flow control purposes. Swirl addition may be beneficial in both divergent flows (e.g. diffusers) and convergent ones (contractions) both in the case of the former it is found to be justified only in special applications where it serves an additional purpose.

Regarding swirl addition in convergent flows, it is found that here the effects are generally much greater than in divergent flows. Our main concern is with the vortex flow modulator which has been the subject of a number of papers, particularly in the Cranfield Fluidics Conferences, but several related devices also require to be considered, e.g. the swirl atomiser and the cyclone separator. Both utilise the radially outward centrifugal force associated with the swirl to separate the components of a two-phase mixture, the denser constituent (such as dust in air) being propelled to the wall and then along it to the throat of the contraction by the action of a secondary current generated in the boundary layer. The heavy component may therefore be collected at the throat and the light component at the other end of the contraction. Such devices have been investigated by ter Linden (1949).

A particularly interesting application of the vortex flow modulator has been developed by Brombach (1974) in which the discharge from a storage reservoir is maintained substantially constant in spite of large variations in depth. The mode of operation, indicated in Fig. 1, is that at low depth the main flow is radially inwards towards the discharge port but is deflected away from the port when an increase in depth triggers the secondary supply. By appropriate sizing and positioning of the trigger orifices, the variation of discharge is limited as shown in the graph. It is interesting to note that the secondary supply is at a lower pressure than the primary flow and that the discharge control is passive with no separate secondary source or external power requirement.

3 DISCUSSION OF RESULTS

3.1 Conical Diffusers with Slot Injection

In this investigation the objective is to assess the merits of slot injection as a means of energizing the boundary layer which grows on the wall of a conical diffuser and hence to obtain a high performance unit with short axial length. Preliminary work was reported earlier (Duggins, 1977) and here the intention is to summarize that and then to present more recent data relating to the quality of the flow discharging from the cone.

The test configuration is shown in Fig.2a and comprises a 30^{o} cone of area ratio 3.265 discharging into a parallel tailpipe. The primary flow has a thin turbulent boundary layer at the cone entrance and the secondary flow is injected through an annular slot parallel to the diffuser axis and located as near to the entrance as was structurally possible. Tests were conducted for a single primary flow-rate corresponding to a Reynolds number in the regime where viscosity effects are negligible. (Incidentally, other tests were performed for cones having smaller angles of divergence and although slightly superior pressure recoveries were measured it was considered that the benefit did not compensate for the considerable increase in cone length).

In Fig. 2b results are presented which show the effects of injection momentum ratio MR (= momentum of the injected fluid ÷ momentum of the primary fluid) and slot area ratio AR (= area of the slot ÷ entry area of the diffuser) on the dimensionless pressure rise C_p up to the cone exit plane, C_p being defined so as to take proper account of the pressure and kinetic energy of the injected fluid. The results relate to five sizes of slot ranging from AR = 0.032 to 0.148 corresponding to annular widths of 0.34 to 1.58 mm in the present rig.

The figure reveals that all the results lie approximately on a single curve which rises from $C_p \simeq 0.28$ at zero injection to a flat peak of $C_p \simeq 0.75$ at MR $\simeq$ 0.14, beyond which additional injection has negligible effect. (The optimum MR value of 0.14 corresponds to mass and velocity ratios of 0.067 and 2.09 respectively for the smallest slot and 0.144 and 0.97 for the largest one.) Hence the effect of optimum injection is to more than double the pressure recovery for zero injection, a far greater improvement than that reported by Neve and Wiransinghe (1978) for the case where swirl is imparted to the incoming flow.

Attention is drawn to the fact that if the same experimental results had been plotted against mass ratio or velocity ratio rather than against momentum ratio, a family of curves would have resulted, one for each size of slot. Therefore one can conclude that it is the *momentum* of the injected fluid which primarily governs the performance of the diffuser, and the corresponding velocity and mass flow are less important. For design purposes, the appropriate size of injection slot in a given application may be estimated from the above optimum value of momentum ratio of 0.14.

An indication of the quality of the discharging flow is given in Fig. 2c where a typical set of velocity profiles are given for a particular slot configuration and for four rates of injection. Increasing the injection rate clearly has the effect of improving the shape of the profile, and the flow separation which is apparent at low values disappears when the injection is sufficient, and a desirable flat profile occurs when the momentum ratio is similar in value to that for maximum pressure recovery. This is to be expected since the boundary layer energization clearly improves simultaneously both the quality of the discharging flow and the magnitude of the pressure recovery.

In conclusion, mention should also be made of the merits of injecting the secondary fluid in a direction which is tangential to the wall of the cone rather than parallel to its axis. (This is the configuration referred to in the Review of Previous Work). A programme of tests was performed to make this assessment and it was found that in every respect the axial mode of injection was superior to the tangential one. The pressure recovery was greater and was achieved with less injection, the discharging flow was more stable and symmetrical, and the geometry of the axial configuration was less complex.

3.2 Circumferential Injection in a Confined Convergent Flow

The configuration is shown in Fig. 3a and is sometimes referred to as a vortex valve or vortex flow modulator. Flow passes through the annular space (5 mm wide in the present rig) between the centrebody and the wall of the contraction, and control of the discharge is achieved by injecting circumferentially a secondary supply of fluid through equi-spaced ports at the entrance to the annulus, adding swirl to the primary flow. The swirling mixture passes through the radius reduction of the contraction causing the circumferential velocity to increase still further because the angular momentum is largely conserved. The radially-outward centrifugal force has a component parallel to the wall in the opposite direction to the flow and it is this force which controls the primary flow and in the limit shuts it off completely.

In the present investigation the objectives are to determine the effects of various geometrical and other parameters on the performance of the device with a view to improving the effectiveness of the flow control by design development. Some results have already been reported in a different context (Duggins & Frith, 1979) and the intention here is to indicate their relevance to the general subject of flow control by secondary injection and to describe some more recent developments.

The experimental results relate to tests in which a degree of pre-swirl was imparted to the primary flow before it entered the annulus and this led to the benefits of injection being advanced, adding to an effect which was already present and reducing the secondary supply and power requirements for a particular degree of flow modulation. It is found that pre-swirl also results in the modulation being

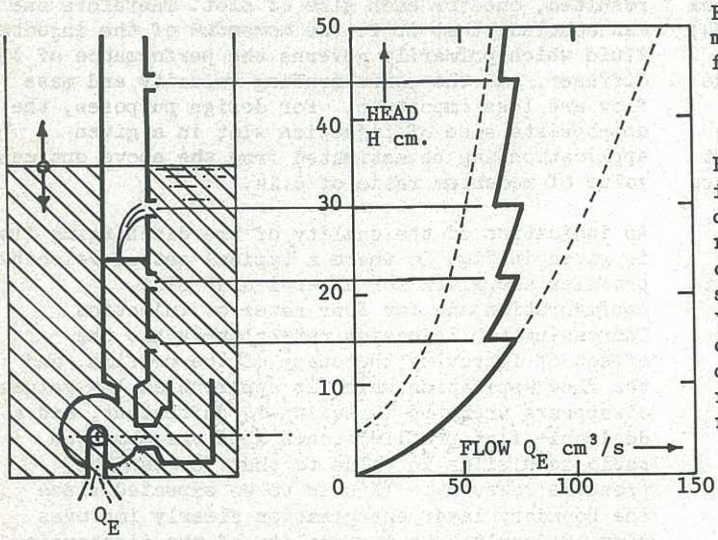


Fig 1 (left) illustrates the use of a vortex modulator to produce a nearly constant discharge from a storage reservoir. (Brombach)

Figs 2a, 2b and 2c (below) show the effects of injection through an axial slot into a 30° conical diffuser. In Fig. 2b the effects of momentum ratio MR and slot size on the pressure recovery coefficient C_p are depicted. The symbols used for slot area ratio c are:- x c = 0.032, + c = 0.043, Y c = 0.068, o c = 0.097. In Fig 2c the corresponding effects are shown of injection rate on flow uniformity at the cone exit. k is the ratio of the injection and primary velocities and r/R is the dimensionless radius.

Fig 2b.

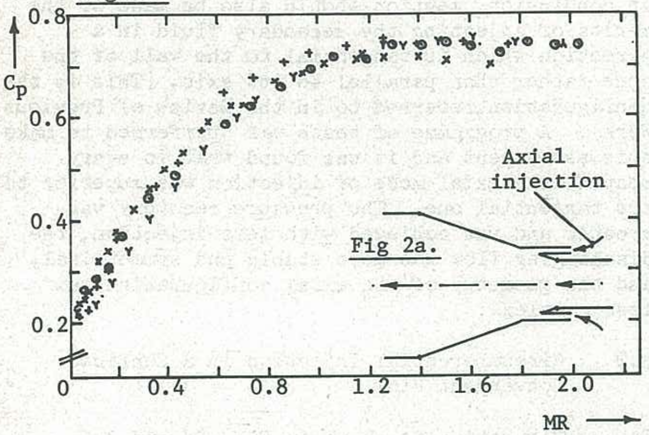
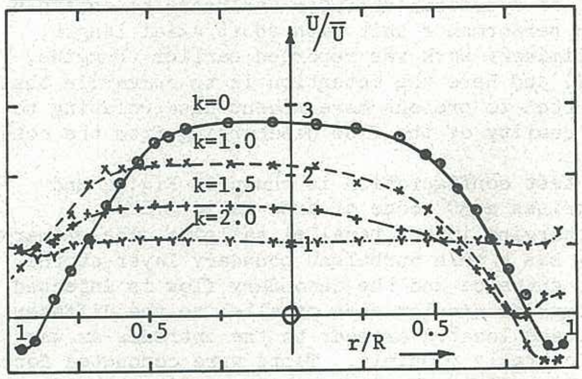


Fig 2c.



Figs 3a, 3b and 3c (below) relate to discharge tests on a vortex modulator. Fig 3b depicts typical control characteristics for three sizes of control port, i.e. diameters d_c of 2, 4 and 6 mm. Fig 3c shows that the data largely collapse to a single curve when plotted against Q_c/d_c. This indicates a specific momentum requirement, independent of port size, for a given degree of modulation of the primary flow.

Fig 3a.

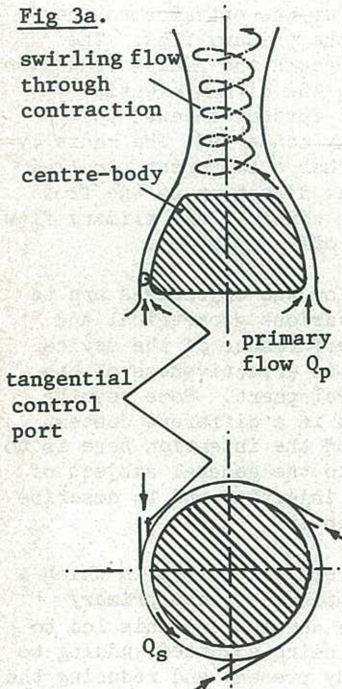


Fig 3b.

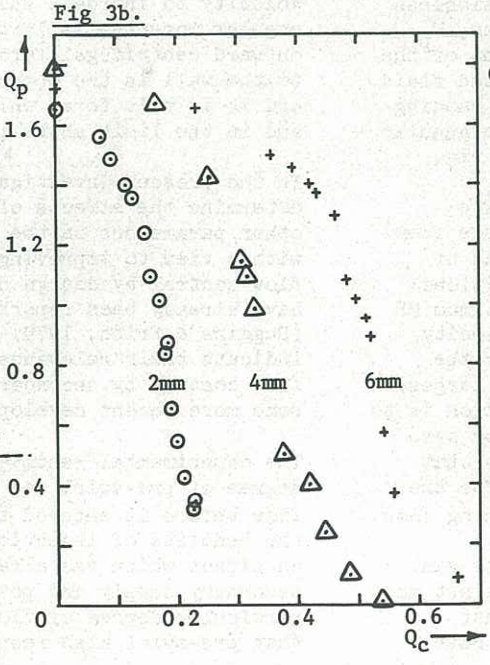
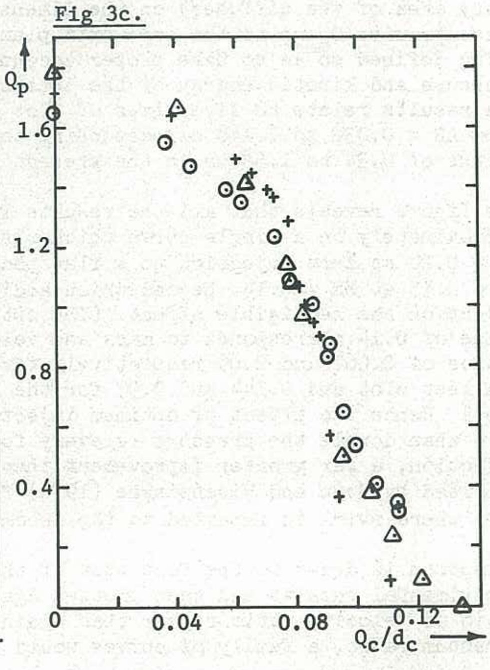


Fig 3c.



less abrupt and this too is clearly desirable with regard to control potential when the primary flow is partially stopped. When it is fully stopped, on the other hand, pre-swirl is of no advantage and the same amount of injection is required for shut-off whether there is pre-swirl or not. A disadvantage of pre-swirl is that it causes both the maximum flow-rate (i.e. at zero injection) and the turn-down ratio to be reduced, the reduction being about 13% in the present tests. On balance however pre-swirl is found to be beneficial for control purposes.

It has been mentioned that the effects of various geometrical parameters are being investigated and one of these is the diameter d_c of the control ports. Fig. 3b depicts typical control characteristics (i.e. primary flow-rate Q_p vs control flow-rate Q_c) for three equi-sized and equi-spaced ports and for d_c = 2, 4 and 6 mm. The primary flow-rate for zero injection is of course independent of port diameter and to achieve a particular degree of flow modulation, the required control flow-rate varies approximately in proportion to d_c. This is illustrated more clearly in Fig. 3c where the same data are shown to collapse to a single curve when plotted to a base of Q_c/d_c rather than Q_c. It is consistent with there being a specific momentum requirement, independent of port size, for a given degree of modulation because the momentum is given by

$$\rho Q_c \cdot \frac{4Q_c}{\pi d_c{}^2} = \frac{4\rho}{\pi}\left(\frac{Q_c}{d_c}\right)^2 \quad \text{(where } \rho \text{ is the density)}$$

and Q_c/d_c is therefore proportional to the square root of the momentum.

In Section 3.1 relating to axial slot injection in conical diffusers for boundary layer energizing, it was shown that the pressure recovery of the diffuser was primarily governed by the momentum of the injected fluid. It is interesting to note this similarity to the case of circumferential injection in a convergent flow where the momentum of the injected fluid is again the most important parameter, in this instance in governing the extent of flow modulation.

Returning to the consideration of the effects of the size of the ports, measurements were also taken to enable the power of the injected fluid to be determined, and in the following table values are given of the power required to reduce the primary flow-rate to half of its initial magnitude.

Port diameter (mm)	2	4	6
Power (W)	43	29	38.

The tabulated values show that the power is similar in magnitude for 2 mm and 6 mm but is about one-third less for 4 mm. Accordingly, although the momentum requirement is independent of diameter, the corresponding power requirement is not and a minimum power condition exists which represents the optimum size of port, probably about 4 mm dia. in the present installation.

Other tests were performed to clarify whether there is an optimum *number* of ports, and six at 60° spacing, three at 120° or two diametrically opposite each other were considered. Numerical results are omitted for the sake of brevity and it suffices to report that the additional geometrical complexity of the six-port configuration appears not to give any compensating benefit, the control power requirements being approximately the same for each number of ports.

Tests have also been carried out using different shapes of centre-body and contraction, for example using contractions much shorter than that depicted in Fig. 3a and with the primary flow entering in a radial rather than an axial direction. The centre-body is important in that it constrains the primary and secondary flows to mix together and its diameter determines the width of the annular gap which surrounds it. In other respects however the geometry was found to have a surprisingly small effect (generally less than 5%) on modulation performance as did the number of ports referred to above. It is reasonable to assume therefore that the results which have been obtained with the present test rig may be used for predicting the performance of other vortex devices where the geometry is rather different.

To conclude this description of our contribution towards improving the understanding of flow control by secondary injection, it is appropriate to mention a further investigation which has been initiated to assess the merits of using the circumferential injection of *air* to control a primary flow of liquid. Preliminary results indicate that such a combination offers considerable promise because the liquid flow-rate discharging from the device can be completely shut-off and control is made easier by the fact that the primary flow-rate is reduced less abruptly than when liquid is used as the control fluid. Such a device is expected to be useful in a number of different applications, particularly if the present work leads to significant design development.

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