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HEAT TRANSFER IN DECAYING SWIRL FLOWS

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Abstract—An experimental study of decaying swirl flows created by tangential vane swirl generators is reported. In the Reynolds number range of 20000–100000, an increase in heat-transfer rates of up to 80 per cent is observed. Of all the tangential vane swirl generator configuration parameters, the width has the largest influence on the heat-transfer rate.

NOMENCLATURE

- C, coefficient in the Dittus–Boelter type relation (equation 1);
- d, diameter of the pipe;
- D, diameter of the swirl generator;
- n, Reynolds number exponent in the Nusselt relation (equation 1);
- N, number of swirl generator vanes;
- Nu, Nusselt number;
- Pr, Prandtl number;
- R, performance criterion (equation 2);
- Re, Reynolds number;
- W, width of the swirl generator.

1. INTRODUCTION

THE USE of swirl flows, both continuous and decaying, has been suggested for augmenting heat-transfer rates in heat exchanger equipments. The purpose of this paper is to present experimental results of heat-transfer studies of decaying swirl flows created by tangential vane swirl generators (Fig. 1). The swirl generator used here consists of straight vanes held between two discs one of which has an opening corresponding to the pipe inner diameter. The vanes are fixed such that they are tangential to the pipe inner diameter. The swirl generator is attached at the pipe inlet. With this arrangement the fluid enters the swirl generator peripherally and is then guided tangentially along the vanes as it enters the pipe. On entering the pipe, the fluid acquires an axial velocity in addition to the tangential velocity and this results in a swirl flow being generated. Since the tangential velocity component is introduced only at the pipe inlet, its magnitude reduces continuously creating a decaying swirl flow in the pipe. This differs from the continuous swirl flow generated by twisted tapes [1] and helical vanes [2].

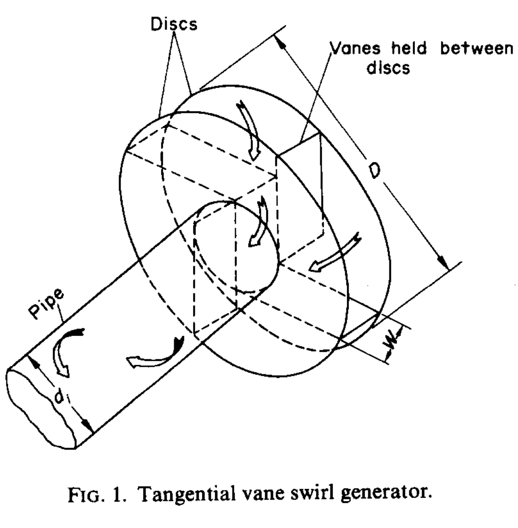

FIG. 1. Tangential vane swirl generator.

Nerezhnyy and Sudarev [3], Migay and Golubev [4] and Ivanova [5] are amongst the relatively few investigators who have experimentally studied the heat-transfer characteristics of decaying swirl flows using different swirl generators. Nerezhnyy *et al.* used short lengths of helical inserts and Ivanova used axial blades, which were placed in the pipe inlet regions. Migay *et al.* have also carried out a theoretical analysis to predict the heat-transfer coefficient based on the evaluation of equivalent friction factors for swirl flows. In the present investigation [6], the heat transfer in decaying swirl flow created by tangential vane swirl generators has been studied. The experimental results were obtained in the turbulent flow region for Reynolds numbers ranging from 20000 to 100000.

2. EXPERIMENTAL SET-UP

Figure 2 shows the schematic diagram of the experimental set-up used in this investigation [6]. The test section was constructed out of a commercial aluminium pipe: ID = 19 mm, OD = 25 mm, length (heated) = 1790 mm. The pipe test-section was enclosed in a steam jacket providing a constant wall temperature boundary condition. The swirl generators were fabricated from 18 gauge galvanized iron sheets and could be easily attached at the inlet to the pipe.

Tap water was used as the working fluid. The test-section wall temperatures and the fluid bulk temperatures were measured using 30 gauge copper–constantan thermocouples. Four thermocouples were used to measure the wall temperature, the first one being located 22 cm from the inlet end followed by the remain-

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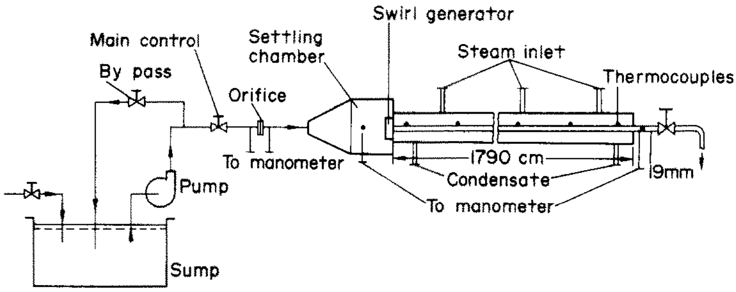

FIG. 2. Schematic diagram of the experimental set up.

ing at equal distances of 45 cm. Each thermocouple was embedded in a 1-cm long groove along the periphery of the pipe with the help of epoxy resin before being led away from the pipe. The bulk temperature of the fluid at the inlet was measured with the help of a thermocouple positioned at the centre of the settling chamber 5 cm ahead of the test-section inlet. The exit bulk temperature was measured at the centre line of the pipe 5 mm from the test section end. All the temperatures were measured to an accuracy of 0·2°C. The pressure losses were measured with U-tube manometers to an accuracy of 0·5 mm with carbon tetrachloride as the manometric fluid. Further details can be found in [6].

3. RESULTS

The swirling motion of the fluid results in a pressure gradient being created in the radial direction thus affecting the boundary layer development. The increased rates of heat transfer in such flows are a consequence of the reduced boundary layer thickness and increased resultant velocity.

The swirl generator (Fig. 1) is characterised by the diameter of the discs, D; width between discs, W (both D and W being related to pipe inner diameter, d); number of vanes, N and the shape of the vanes (straight or curved). In this investigation, the influence of D, W, and N on swirl flow heat-transfer rate has been determined for straight vane swirl generators only. The ratio $Nu/Pr^{0.4}$ has been chosen for representing the heat-transfer characteristics so as to provide a basis for comparison with axial flow results.

The curves represented in Figs. 3–5 are based on correlations of the form

$$\frac{Nu}{Pr^{0.4}} = C\,Re^{n}. \tag{1}$$

These fitted the experimental data within ±10 per cent. The experimental error in the evaluation of Nusselt number was estimated to be ±5 per cent. The Reynolds numbers were based on the bulk properties and the pipe inner diameter. The values of the constants C and n are indicated in the figures.

Figure 3 shows the influence of width of the swirl generator on the average Nusselt number for the same diameter ($D = 5d$) and same number of vanes ($N = 4$). Also plotted for comparison are the results obtained for axial flow (no-swirl) and the Dittus–Boelter [7] correlation. The axial flow values obtained in the present

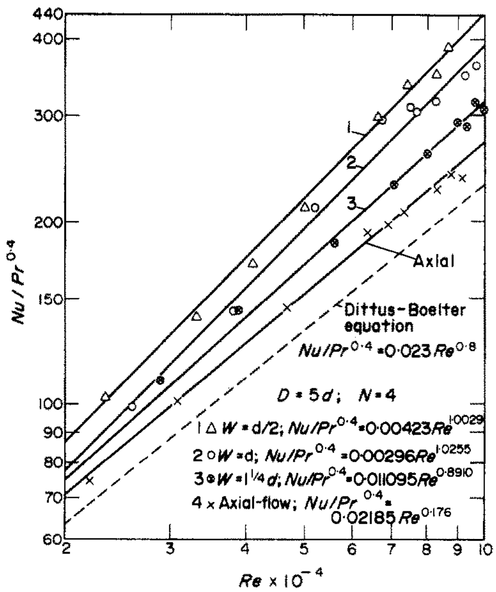

FIG. 3. Effect of swirl generator width on the average Nusselt number.

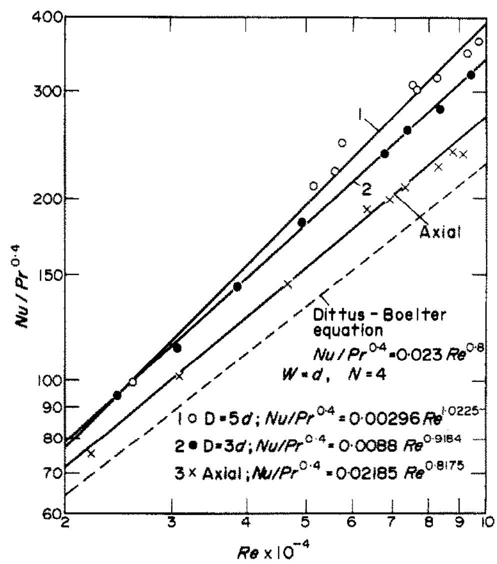

FIG. 4. Effect of swirl generator diameter on the average Nusselt number.

investigation are from 8 to 20 per cent higher than the values predicted by the Dittus–Boelter equation. This is attributed to the high degree of turbulence created by the sudden contraction and the sharp ended opening

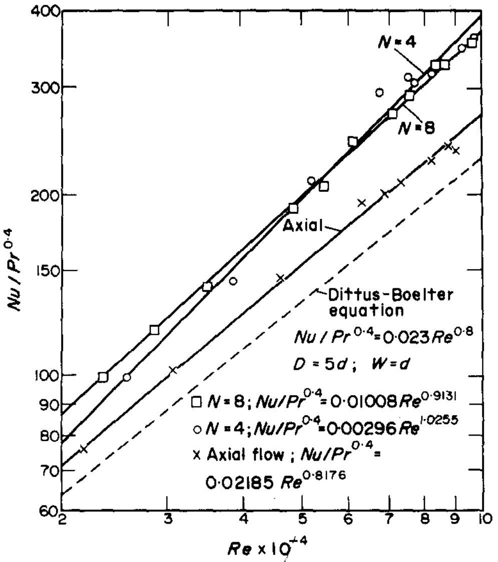

FIG. 5. Effect of number of vanes of the swirl generator on the average Nusselt number.

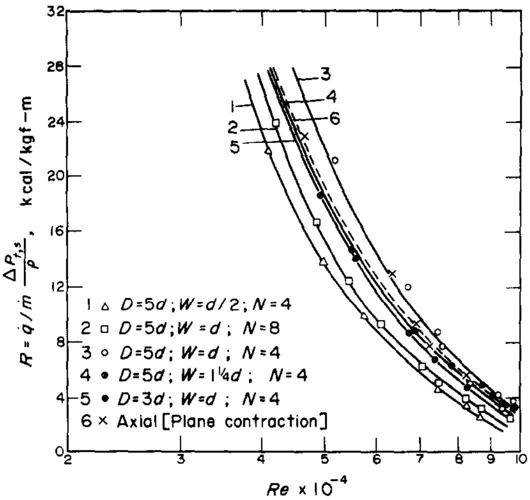

FIG. 6. Ratio of heat-transfer rate to pumping power, R, for different swirl generators.

at the entrance to the test-section. It is seen from Fig. 3, that the Nusselt number increases as the width of the swirl generator decreases, the increase being more predominant at higher Reynolds numbers. For the smallest width ($W = d/2$), the increase in heat-transfer rate ranges from 30 to 80 per cent over the values obtained for axial flow in the Reynolds number range of 20 000–100 000. The increases in heat transfer with reduced width is due to the higher swirl intensity imparted to the flow at the pipe inlet.

Figure 4 shows the influence of the diameter of the swirl generator for the same width ($W = d$) and number of vanes ($N = 4$). It is seen that, the use of a larger diameter ($D = 5d$) results in a greater improvement in the heat-transfer rate and that this influence is also predominant at higher values of the Reynolds number. This is due to the fact that with a larger swirl generator diameter ($D = 5d$), the fluid is guided over a longer length of the vanes and the fluid particles have better chance of acquiring the swirl velocity component before entering the pipe. Moreover the influence of the swirl with larger intensity may be expected to be carried over a longer length of the pipe.

Figure 5 shows the influence of the number of vanes ($N = 4$ and 6) of the swirl generator for the same diameter ($D = 5d$) and width ($W = d$). It is seen that the larger number of vanes ($N = 8$) have a greater influence on the heat-transfer rate in the lower Reynolds number range. However for Reynolds numbers greater than 55 000, the swirl generator with the smaller number of vanes ($N = 4$) shows a slight improvement over the one with the larger number of vanes ($N = 8$). However these changes are small as compared to the effect of the width.

Heat-transfer augmentative methods generally influence a number of factors like initial, operational and maintenance costs, safety, reliability, surface area and pumping power. It is therefore difficult to prescribe a single criterion for rating the value of an augmentative method. Bergles *et al.* [8] have developed a number of performance criteria to take into account the various factors. In this investigation, the performance criterion based on pumping power defined by

$$R = \frac{\text{Heat-transfer rate}}{\text{Pumping power}} \tag{2}$$

has been used to characterise the relative merits of the swirl generator in augmenting the heat-transfer rate. This parameter plotted for the various swirl generator configurations tested is shown in Fig. 6. The presence of the swirl generator results in additional pressure loss, apart from that occurring in the pipe due to the swirling flow. Hence the parameter R was based on the total pressure losses both in the swirl generator and the pipe. It is seen that one of the curves, that corresponding to the swirl generator with $D = 5d$, $W = d$ and $N = 4$, lies above the axial flow curve and indicates an improvement in performance of about 10 per cent.

4. CONCLUSIONS

1. Tangential vane type swirl generators can be used to augment heat-transfer rates. In the range of Reynolds from 10 000 to 100 000 an augmentation of up to 80 per cent was obtained with a constant wall temperature boundary condition.
2. Of all the parameters characterising the swirl generator configuration, the width has the largest influence on the heat-transfer augmentation.
3. From the point of view of the performance criterion R, the swirl generator with $W = d$, $N = 4$ and $D = 5d$ provides a performance better than that obtained when no swirl generator is present.

The swirl generators are easy to fabricate and adopt. Higher augmentation can be expected with curved vanes as they aid the development of larger swirl intensities.

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TRANSFERT DE CHALEUR DANS LES ECOULEMENTS TOURBILLONNAIRES EN DECROISSANCE

Résumé--On présente une étude expérimentale d'écoulements tourbillonnaires en décroissance créés par des générateurs de tourbillons à ouverture tangentielle. Dans le domaine des nombres de Reynolds allant de 20000 à 100000, on a observé un accroissement du transfert de chaleur atteignant 80 pour cent. De tous les paramètres géométriques du générateur de tourbillons à ouverture tangentielle, la largeur a une influence dominante sur le taux de transfert de chaleur.

WÄRMEÜBERGANG IN EINER STRÖMUNG MIT ABKLINGENDER VERWIRBELUNG

Zusammenfassung—Es wird eine experimentelle Studie über von einem Tangential-Rührer erzeugte abklingende Wirbelströmung beschrieben. Im Bereich der Reynolds-Zahlen von 2.10^4 bis 10^5 wird eine Zunahme des Wärmeübergangs bis zu 80% beobachtet. Von allen Parametern, die den Tangential-Rührer charakterisieren, hat die Breite den größten Einfluß auf den Wärmeübergang.

ТЕПЛООБМЕН В ЗАТУХАЮЩИХ ЗАВИХРЕННЫХ ТЕЧЕНИЯХ

Аннотация — Описывается экспериментальное исследование затухающих завихренных потоков, создаваемых тангенциальными лопаточными турбулизаторами. В диапазоне чисел Рейнольдса от 20 000 до 100 000 наблюдалось увеличение скорости теплообмена до 80%. Из всех геометрических параметров тангенциальных лопаточных турбулизаторов, наибольшее влияние на скорость теплообмена оказывает ширина.