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Local heat transfer downstream of an asymmetric abrupt expansion and cavity in a circular tube

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ABSTRACT

This study is concerned with measuring local heat transfer downstream of an asymmetric abrupt expansion and an asymmetric abrupt expansion followed by an asymmetric abrupt contraction (called "asymmetric cavity") in a circular tube at a uniform wall temperature. The effects of geometry and three-dimensionality of the flow caused by asymmetric expansion on heat transfer characteristics are also examined. The flow just upstream of the expansion is unheated and fully developed at the entrance to the heated asymmetric abrupt expansion region. Local heat transfer coefficients are measured using a specially designed isothermal heat flux sensor. Measurements for the asymmetric abrupt expansion are made at a small to large diameter ratio of $d/D = 0.4$ and 0.533 for Reynolds numbers of $\mathrm{Re_D} = 17{,}300$ and 21,900, respectively. The eccentricities of the tube axis (e/D) are 0.25 and 0.17 for $d/D = 0.4$, and 0.195 and 0.065 for $d/D = 0.533$. For the asymmetric cavity, all tests are made at $d/D = 0.4$ and $\mathrm{Re_D} = 17{,}300$ with various cavity lengths for $e/D = 0$ and 0.25, respectively. For both cases, the variations of local Nusselt number are observed along the wall of downstream circular tube at several angular positions around the tube circumference. In general, the local Nusselt numbers downstream of an asymmetric abrupt expansion are substantially higher than the fully developed values for the range of Reynolds numbers, diameter ratios and eccentricities investigated, due to high turbulence and mixing action in the recirculation region. And the maximum Nusselt numbers occur between 10 and 15 step heights from the expansion step. The Nusselt number distributions for the asymmetric cavity show a dramatic increase to the maximum values as the downstream region of the cavity is approached. This behavior is attributed to a periodic vortex shedding, subsequent impingement on the downstream corner region of the cavity and three-dimensionality effects which cause an increase in turbulence intensity.

1. Introduction

Turbulent heat transfer characteristics downstream of an abrupt expansion and in a cavity of the circular tube bring together geometric simplicity with a complex flow behavior owing to the separation, recirculation and reattachment of the separated flow caused by abrupt changes in flow area. Such flows occur in many industrial applications, including heat exchangers, combustors of gas turbine engines, nuclear reactors, turbine flow passages, electronic circuitry, and high performance propulsion systems. These flows are particularly interesting because they are associated with a large variation of the local heat transfer coefficient and substantial heat transfer augmentation.

One of the earliest experimental studies of the heat transfer in regions of separated and reattached flows inside of tubes and ducts appears to have been undertaken by Boelter et al. [1]. They investigated the effect of orifice-induced separation on heat transfer to air flowing through a steam-jacketed tube under essentially a uniform wall temperature condition.

Ede et al. [2] reported local heat transfer coefficients downstream of an abrupt expansion with a diameter ratio d/D of 0.5. Their results show that the maximum Nusselt numbers near the reattachment point are about three times the fully developed Nusselt number.

Later, Zemanick and Dougall [3], Baughn et al. [4], and Krall and Sparrow [5] studied turbulent axisymmetric abrupt expansion flow with a uniform wall heat flux boundary condition. All of these studies found considerable augmentation of the heat transfer coefficients with peaks occurring near the reattachment point.

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Nomenclature

A_s	surface area of Ni/Cr ribbon in the heat flux sensor [m^2]
C_e	thermal conductance between Ni/Cr ribbon and aluminum walls [W/K]
d	upstream tube diameter [m]
D	downstream tube diameter in the abrupt expansion region [m]
e	eccentricity from the tube axis [m]
h	local heat transfer coefficient [W/m^2 K]
H	step height: $(D-d)/2$ [m]
H/L	cavity aspect ratio
k_a	thermal conductivity of air [W/mK]
L	cavity length [m]
Nu	local Nusselt number
Nu_{fd}	fully developed Nusselt number
Nu_m	mean Nusselt number
Pr	Prandtl number of the air
q	power input to the Ni/Cr ribbon in the heat flux sensor
R_s	resistance of Ni/Cr ribbon in the heat flux sensor [Ohm]
Re_d	Reynolds number based on the upstream tube diameter
Re_D	Reynolds number based on the downstream tube diameter
Re_L	Reynolds number based on the cavity length
r	radial position from the upstream tube axis [m]
T_b	air bulk temperature [°C]
T_s	sensor (Ni/Cr ribbon) surface temperature [°C]
T_w	wall (aluminum) temperature [°C]
V_s	voltage across the Ni/Cr ribbon in the heat flux sensor [V]
x	axial position downstream of the abrupt expansion step [m]

Zemanick and Dougall [3] published results of detailed experiments on the turbulent heat transfer downstream of an abrupt expansion in a circular tube using air. They imposed a nearly uniform heat flux boundary condition downstream of the abrupt expansion by using electrically heated tube. Baughn et al. [4] found out later that heat transfer results by Zemanick and Dougall [3] had some errors due to wall axial conduction in the tube as well as flow compressibility effects caused by too large temperature difference between the wall and the inlet flow.

Baughn et al. [4] launched the experiments to improve previous results by Zemanick and Dougall [3] and were able to obtain low uncertainty heat transfer data by significantly reducing both the wall conduction and compressibility effects. In order to accomplish this, firstly, they created a nearly perfect uniform wall heat flux boundary condition by minimizing axial conduction loss in the tube wall that is made up of the cast acrylic tube of low thermal conductivity and an electrically heated thin gold film on a polyester substrate sheet. Secondly, the tube wall was heated such that a temperature difference between the wall and the inlet flow was about 10 °C which was high enough for low uncertainty heat transfer data and low enough for no significant change of flow properties. The experiments were tested at small to large tube diameter ratios ranging from 0.267 to 0.8 and Reynolds number from 5300 to 87,000. Their results provided a clear evidence of a secondary recirculation near the expansion corner region where no previous measurements had been reported.

Krall and Sparrow [5] have investigated turbulent heat transfer at the downstream of an axisymmetric abrupt expansion in an orifice. They created a uniform wall heat flux boundary condition by passing an electric current through the stainless steel tube. The experiments were carried out at Reynolds numbers ranging from 10,000 to 130,000 for orifice-to-tube diameter ratios from 0.25 to 0.67. The results showed that the peak Nusselt numbers downstream of the orifice were approximately 3–9 times greater than the fully developed values. The increase in the peak Nusselt number relative to the fully developed value was accentuated as the degree of separation became greater (i.e., smaller orifice-to-tube diameter ratio). For example, for a Reynolds number of 25,000 and a Prandtl number of 3, the ratio of the peak Nusselt number to the fully developed value increased from 3.7 to 6.7 as the orifice-to-tube diameter ratio changed from 0.67 to 0.25.

Khezzar et al. [6] carried out an experimental investigation of the water flows through one axisymmetric and two asymmetric circular sudden expansions with area ratios of 3.06 and eccentricities of the pipe axes of 0, 5, and 15 mm. Reattachment lengths were determined over the Reynolds numbers ranging from 120 to 40,000 for all three cases. The presence of vortex rings downstream of plane of expansion at transitional Reynolds numbers was revealed by flow visualization. It was shown that asymmetric inlet conditions strongly influenced the distribution of mean and turbulence quantities downstream of the expansion, resulting in three-dimensional reattachment.

Lee et al. [7] conducted numerical and experimental study of heat transfer at axisymmetric abrupt expansion followed by an abrupt contraction in a circular tube with a uniform wall temperature. The experimental results revealed that the maximum Nusselt numbers occurred between 9 and 12 step heights from expansion step. Their numerical results were in a good agreement with the experimental results.

Rusak and Hawa [8–10] carried out a weakly nonlinear analysis of the bifurcation [8], studied the effect of a slight asymmetry of the channel geometry on the flow behavior [9], and analyzed the interplay of viscous dissipation and convection of perturbations for increasing jet Reynolds number [10]

More recently, as an effort to enhance the heat transfer rate, various techniques which cause the augmentation of three-dimensionality of flow behavior and turbulent intensity have been applied to abrupt expansion geometries.

Guo et al. [11] carried out three-dimensional, time-dependent calculations using the finite volume method and the very large eddy simulation technique with standard $\kappa-\varepsilon$ model to simulate the turbulent swirl flow in an axisymmetric abrupt expansion with an expansion ratio of 5.0 for a Reynolds number of 100,000 and swirl numbers from 0 to 0.48. They reported that the flow was unstable over the entire swirl number range considered, and a large-scale coherent structure precessed about the centerline. Visualization of the instantaneous flow fields showed the spiral nature of the flow in terms of the shape of the jet and the vortex core. They also learned that increasing swirl intensity can enhance the jet spreading rate and reduce the precession amplitude of the precessing vortex cores (PVC).

Vanierschot and Van den Bulck [12] carried out a theoretical study on the influence of swirl on the reattachment length in an axisymmetric abrupt expansion. A scale analysis of the equations of motion reveals that the reattachment length decreases with increasing swirl.

Zohir et al. [13] investigated the heat transfer characteristics and pressure drop for turbulent flow in an abrupt expansion pipe equipped with propeller type swirl generator or spiral spring with various pitch ratios. Their experiments were conducted for