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Heat transfer characteristics in a sudden expansion pipe equipped with swirl generators

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ABSTRACT

This investigation is aimed at studying the heat transfer characteristics and pressure drop for turbulent airflow in a sudden expansion pipe equipped with propeller type swirl generator or spiral spring with several pitch ratios. The investigation is performed for the Reynolds number ranging from 7500 to 18,500 under a uniform heat flux condition. The experiments are also undertaken for three locations for the propeller fan ($N = 15$ blades and blade angle of 65°) and three pitch ratios for the spiral spring ($P/D = 10$, 15 and 20). The influences of using the propeller rotating freely and inserted spiral spring on heat transfer enhancement and pressure drop are reported. In the experiments, the swirl generator and spiral spring are used to create a swirl in the tube flow. Mean and relative mean Nusselt numbers are determined and compared with those obtained from other similar cases. The experimental results indicate that the tube with the propeller inserts provides considerable improvement of the heat transfer rate over the plain tube around 1.69 times for $X/H = 5$. While for the tube with the spiral spring inserts, an improvement of the heat transfer rate over the plain tube around 1.37 times for $P/d = 20$. Thus, because of strong swirl or rotating flow, the propeller location and the spiral spring pitch become influential on the heat transfer enhancement. The increase in pressure drop using the propeller is found to be three times and for spiral spring 1.5 times over the plain tube. Correlations for mean Nusselt number, fan location and spiral spring pitch are provided.

1. Introduction

Sudden expansion flows bring together geometric simplicity with a complex flow behavior because of the interaction of a recirculation region and a jet in a confined duct, but their relevance also stems from the fact that they often occur in industry. Many applications of Newtonian sudden expansion flows pertain to the turbulent flow regime, because they involve low viscosity fluids, such as air or water. Examples are ventilation flows, flows of relevance to aeronautics, and to combustion. However, in many other instances, where high-viscosity fluids and/or tiny geometries are involved, as in glass melting, polymer processing flows, and some mixing flows, their characteristics can be laminar. In pressure drop calculations in piping networks, it is engineering practice to consider that the flow is fully developed in the straight pipes or ducts, with all other effects, such as flow distortions and redevelopment in fittings, curves, and other elements, introduced via their respective local loss coefficients (Oliveira and Pinho, 1997). The flow through a sudden expansion produces mixing rates, and subsequently, heat transfer coefficients, which are substantially higher downstream of the expansion than those, which would be obtained at the same, Reynolds number in the entrance region of a pipe. This enhancement in diffusion rates occurs in spite of a recirculation region extending about nine step heights downstream from the expansion. In this recirculation region, mean velocities are typically only 10% as high as those found in the core flow, suggesting that the principle mechanism for heat transfer augmentation is the high turbulence levels which are present in fact, very high levels of turbulent kinetic energy are generated by sheering as the core flow issues into the larger pipe. Because length scales are large in the shear layer, the turbulent kinetic energy generated there dissipates relatively slowly, maintaining much larger levels than would be found in ordinary pipe flow were no such internal shear layer exists. With high levels of turbulence kinetic energy, diffusion rates are elevated and the thickness of the viscosity-dominated sublayer is reduced, resulting in high rates of heat transfer between tube wall and mean flow (Dellenback et al., 1987).

Heat transfer enhancement may be achieved by numerous techniques, and these techniques can be classified into three groups: passive, active and compound techniques (Bergles, 1997). The passive techniques, such as swirl flow devices, treated surfaces, rough

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Nomenclature

Variables

C_p	specific heat capacity of the fluid, J/kg k
D	test section pipe diameter, m
d	upstream smooth pipe diameter, m
f	friction factor
H	step height, $H = 0.5(D - d)$, m
h_x	local coefficient of heat transfer, W/m^2 K
k_m	thermal conductivity of the fluid, W/m K
L	test section pipe length, m
$\dot{m}$	air mass flow rate, kg/s
Nu_m	mean Nusselt number for sudden expansion
Nu_x	local Nusselt number for sudden expansion
Nu_s	the fully developed Nusselt number at constant mass flow rate
Nu_s^*	the fully developed Nusselt number at constant pumping power
q_o	total heat flux, W/m^2
Q	input heat, W
Q_{loss}	heat loss through the insulation, W
Q_{net}	net of heat transferred to the test section, W
Re	Reynolds number
T_{bi}	fluid bulk inlet temperature, °C
T_{bo}	fluid bulk outlet temperature, °C
T_{bulk}	fluid bulk temperature, °C
T_{bx}	bulk temperature of the fluid at section x, °C
X	distance measured from the leading edge of sudden expansion, m

surfaces, extended surfaces, displaced enhancement devices, coiled tubes, surface tension devices and additives for fluids; do not require direct application of external power. Whereas the active techniques, such as mechanical aids, surface vibration, fluid vibration, electrostatic fields, suction or injection and jet impingement, require an external activator/power supply to bring about the enhancement. In the compound techniques, such as rough surface with a twisted tape swirl flow device and two or more of the active or passive techniques may be utilized simultaneously to produce an enhancement that is much higher than the techniques operating separately.

Swirling flow in pipes can be provided by many kinds of swirling generators. This may be classified into two essential types: continuous swirl flow and decaying swirl flow. In continuous swirl flow, the swirling motion persists over the whole length of the duct, while in decaying swirl flow; the swirl is generated at the entry section of the duct and decays along the flow path. Continuous swirling flow in a duct can be generated by inserting coiled wires, twisted tapes, and helical vanes or by making helical grooves in the inner surface of the duct. While decay swirling flow is found when we use snail entry, guided or propeller fan in the entry, tangential entry and short length of helical or twisted tape in the entry. Swirl flow devices are designed to impart a rotational motion about an axis parallel to the flow direction to the bulk flow and are one of the passive enhancement techniques used for increasing the rate of heat transfer (Kreith and Bohn, 1993). Swirl flows are found in nature, such as tornadoes, and are utilized in a very wide range of applications, such as cyclone separators, Ranque–Hilsch tubes, agricultural spraying machines, heat exchangers, gasoline engines, diesel engines, gas turbines and many other practical heating devices (Gupta et al., 1984). Swirl flow is the descriptive term for a fluid flow in which the tangential component of the mainstream velocity is a significant contribution to the resultant velocity. Swirl flows may be classified into three groups depending upon characteristic velocity profiles: curved, rotating and vortex flow (Razgaitis and Holman, 1976). These velocity profiles are different, depending upon the particular flow geometry and swirl generation methods. Curved flow is produced by a stationary boundary, causing a continual bending of the local velocity vector, and complex secondary flows with an appreciable velocity component normal to the instantaneous osculating plane are generated. Curved flows can be generated by inserting coiled wires, twisted tapes and helical vanes into the pipe, by coiling the tube helically or by making helical grooves in the inner surface of the duct. Curved flow is also called “continuous swirl flow”. Rotating flow is generated by a rotating boundary, either confining the flow (as for a rotating tube) or locally influencing the flow field (as for a spinning body in a free stream). Vortex flow arises when a flow with some initial angular momentum is allowed to decay along the length of a tube (Razgaitis and Holman, 1976). Vortex flow is also called “decaying swirl flow”. Decaying swirl flows are generated by the use of tangential entry swirl generators and guided vane swirl generators. Tangential entry of the fluid into a duct stream can be achieved by using a single tangential inlet duct or more than one tangential entry (Yapýcý et al., 1992).

Guided vane swirl generators may be grouped into two types: radial guide vane and axial guide vane. Axial vane swirl generators consist of a set of vanes fixed at a certain angle to the axial direction of the duct, which give a swirling motion to the fluid (Blackwelder and Kreith, 1970; Narazhnyy and Sudarev, 1971; Sudarev, 1972; Klepper, 1973; Baker et al., 1974; Yowakim and Kind, 1988). Generally, the vanes are mounted on a central hub, and they occupy space in an annular region. Even one single helical vane or twisted tape can be used as a means of generating decaying swirl flow. Radial guide vane swirl generators are generally mounted between two disks, and the vanes are so constructed as to be adjustable to obtain the desired initial degree of swirl. Radial generators are capable of generating much more intense swirls, and they cause more complex velocity profiles than axial generators, since the flow direction must change from radial inward to axial downstream, which can occur either abruptly or by means of a fairing section. An inserted centre body (deflecting element) can be used in radial generators whose function is to deflect the flow into the pipe as smoothly as possible.

Many investigators (Dervage et al., 1959; Kelvey et al., 1960; Steele et al., 1961; Loosley et al., 1961; Lavan and Fejer, 1966; Yajnik and Subbaiah, 1973; Clayton and Morsi, 1984; Algifri et al., 1988; Kitoh, 1991, 1984; Kito and Kato, 1984; Yilmaz et al., 1999, 2003; Algifri et al., 1988; Bali, 1998) have studied decaying swirl flow in a circular pipe. In the heat transfer, studies on decaying swirl flow in the Thermo-mechanics Research Laboratory of the Aerospace Research Laboratories (ARL) (Dervage et al., 1959; Kelvey et al., 1960; Steele et al., 1961; Loosley et al., 1961), radial swirl generators with fixed guide vanes were used. The guide vane apparatus utilized 18 fixed vanes oriented nearly tangential to the vortex generator circumference and provided a simple transition section by means of a polished wall fairing of radius 2.54 cm. Lavan and Fejer (1966) examined the velocity profiles for a confined vortex with induced flow/radial generator using adjustable guide vanes and a transition section employing an internal wall fairing with an insert plug with the exit of vortex tube directed into a radial diffuser section. Yajnik and Subbaiah (1973) investigated the