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The effects of swirling decaying flow towards pipe entry length and heat transfer in an annular pipe

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ABSTRACT

The hydrodynamic entry length of axial pipe flow has been studied extensively over the years. Entry length is used to identify range of fully developed flows as commonly used in many practical engineering applications (e.g. Moody's chart). For laminar axial pipe flow, the hydrodynamic entry length has been investigated by Kays, Shah and Bhatti (KSB) ($L_h = 0.056\ ReD_h$). In contrast, several approximations exist for fully turbulent flows (i.e. 10 D_h–150 D_h). Through theoretical and numerical investigations, the hydrodynamic entry length for swirling decaying pipe flow in the laminar regime is investigated. It is found that, the development length $\mathrm{L_h}$ for the axial velocity profile is reduced when a rotational component is added to the mean flow. The reduction in the hydrodynamic length is found to be proportional to the inlet swirl angle θ and the magnitude of the rotational component. Results indicate that a modification can be made on the KSB equation for two-dimensional swirling annular pipe flow. This research also investigates the effect of the local swirl number and Reynolds number on the steady and unsteady heat transfer inside an annular pipe. The existence of the jet effect near the exit of the swirl vane altered the behaviour of the local heat transfer coefficient in the axial direction (along the pipe) for $z = 0$ mm to $z = 40$ mm. The heat transfer coefficient for the 30° vane angle is found to increase after $z = 0$ mm to a maximum value before decaying nonlinearly, whereas, for the 45° and 60° vane angles, the heat transfer coefficient decreases nonlinearly starting from the vane exit. It is found that, for low Re, T_s changes linearly over the course of the cooling zone for all vane angles. With increasing Reynolds number, the behaviour of the cooling curve changes from linear to nonlinear. Overall, the cooling time is found to be inversely proportional to Re. With increasing vane angle, the overall swirl number S along the pipe decreases, thus, reducing the overall swirling momentum in the annular pipe, leading to a lower heat diffusion rate. It is found that the dependency of the temperature of the solid rod T_s on Re is decreasing as Re increases.

1. Introduction

The hydrodynamic entry length of axial pipe flow has been well studied over the years [1–3]. The predictability of the entry length in pipes has benefited many practical engineering applications e.g. the estimation of wall friction factor in the fully developed regions through the Moody Diagram [4], heat transfer for fully developed pipe flows [5], etc. The entry length for pipe flow is characterised by the boundary layer and the irrational core region and for the case of laminar axial flow, the velocity profile attains a fully developed state $\frac{\partial u(r,x)}{\partial x} = 0$, at L_h, the hydrodynamic entry length. The equation has been limited to axial flow pipe flows. It would be an interesting attempt to adapt such equations to swirling/vortex pipe flow.

Although there are several studies [3,6] on the entry length for an axial flow in pipes, but there is no work addressing the prediction of the entry length for a fully developed swirling flow. The importance of this cannot be neglected as knowing the entry length is essential to determine which heat transfer to be used at the specific location, using the existing relations developed for axial flow may lead to serious errors on the prediction of heat transfer coefficient.

Swirling flow in pipes and ducts are found in many engineering applications [7,8] e.g. swirl tubes, vortex tubes, hydrocyclones, swirl combustors, pipe lines, mixers, flow guiders, etc. The work on various passive swirlers can be found in literatures [9–13]. Ho

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Nomenclature

Symbols

A	area, m^2
A^*	aspect ratio, $A^* = z/D_h$
c	heat capacity, $J \cdot kg^{-1} \cdot K^{-1}$
C_ε	k-ε model constant = 1.92
C_μ	k-ε model constant = 0.09
D	diameter, mm
e	diametric clearance ($D_h/2$), mm
h	heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
k	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
k_e	turbulent kinetic energy, m^2/s^2
L	length, mm
Nu	Nusselt number, $Nu = hDh/k$
P	pressure, *Pa*
Pr	Prandtl number, $Pr = \mu Cp/k$
q''	heat flux, Wm^{-2}
R, r	radius, mm
Re	Reynolds number, $Re = \rho U D_h/\mu$
S	Swirl number, $S = v/w$
T	temperature, °C
t	time, s
u,v,w	velocity, $m \cdot s^{-1}$
V	volume, m^3

Greek

α	thermal diffusivity of solid, $m^2\ s^{-1}$
ε	turbulence dissipation rate, $m^2\ s^{-3}$
μ	dynamic viscosity, $kg\ m^{-1}\ s^{-1}$
ρ	density, $kg \cdot m^{-3}$
θ	vane angle
σ_ε	turbulence model constant for k-ε equation = 1.3
σ_k	turbulence model constant for k-ε equation = 1
ω	rotational speed, s^{-1}

Subscripts and super scripts

eff	effective
f	fluid
h	hydraulic
i	inner diameter
0	initial
o	outer diameter
p	constant pressure
res	resultant
s	solid
t	turbulent
v	vane angle
x,y,z	Cartesian component
r,θ,z	cylindrical component

et al. [14–16] investigates the flow dynamics of swirling decaying flows in an annular pipe using both experimental and numerical techniques. The use of axial swirl vanes produced decaying swirl flows that can be defined through the swirl number *S* as functions of *Re*, pipe length and the vane angle.

Heat transfer enhancement methods remain as core area in thermo-fluids research activities [7,8,17–22]. In particular, vortex flow i.e., swirling flow has been of interest in many different fields e.g., processing vortex core (PVC) in combustion chambers [23–26], swirl tubes [12,27,28], swirl generators [29,30], etc.

Detailed reviews and work on swirling flows can be found in [8,9,31–37]. Swirling decaying flow produced by axial swirl vanes can be found in the work of Zhang et al. [38]. Zhang used the algebraic Reynolds stress model (ASM) developed in [38–40] to investigate the heat transfer characteristics in an annular duct under swirling turbulent flows. The flow of hot air is simulated numerically using the SIMPLE algorithm. The two-dimensional time averaged model is used to investigate the effect of the inner to the outer radius (r_i/r_o) ratio, swirl number and the inlet axial velocity towards the overall heat transfer of the annular system. The numerical model is simulated with the inner and outer wall at isothermal temperatures to cool down swirling hot air created from an inlet swirler with a vane angle of α. The following general conclusions were obtained: (1) An increase in swirl number or the axial inlet velocity will increase the heat transfer coefficient of both the local Nusselt number at the inner and outer wall and thus the overall heat transfer coefficient of the annular system. Ahmadvand et al. [11] conducts an experimental and CFD study on the steady-state heat transfer and fluid flow characteristics of swirling decaying flow generated using axial swirl vanes in a pipe. The study is conducted for an inlet Reynolds number ranging from 10,000 to 30,000 for three different blade angles (30°, 40° and 60°). The thermal performance is found to increase between 50 and 110% depending on the vane angle.

Axial swirl vanes are placed at the beginning of pipes or annular pipes to improve heat transfer [10,16,41] or to facilitate in mass transfer [42,43]. Various works have contributed to flows in the laminar [16,37] and the turbulent flow regimes [11,16,40]. Both decaying nature [44] and pressure drop remains the main challenge for axial inlet swirlers. The decaying nature has led to the incorporation of cascaded swirlers [45] or the use of twisted tapes [34] which may contribute to additional pressure losses and the hindrance of uniform flow.

In the work of Ho et al. [8,14–16] the authors studied the effect of different Swirl and Reynolds number towards the flow behaviour in an annular pipe. The authors, evaluated the effect of swirl angle and Reynolds number towards the flow field in an annular pipe. The novelty of this work is to apply the numerical model developed in [8,16] to investigate the effect of swirling flow towards the hydrodynamic entry length L_h inside an annular pipe and to study the effect of the vane angle (θ_v) and Reynolds number (*Re*) towards both steady and transient heat transfer.

2. Numerical model setup

The physical experimental setup in [16] for decaying flows is modelled using the commercial codes from ANSYS CFX 12.0. The flow field for different vanes is investigated in [15]. The focus of this work is to investigate numerically the effect of swirling flow towards the hydrodynamic entry length, L_h, steady and unsteady heat transfer. In-depth information on the simulation model can be found in [8,14–16]. The equations (Eqs. (1)-(6)) are solved for three dimensional turbulent flow using the two equation *k*-ε model while equations (Eqs. (1)-(4)) are solved for three dimensional laminar flow ($\mu_{eff} = \mu$). For unsteady heat transfer, the time dependent equivalent of Eqs. (1) and (2) are used.

The simplified steady-state mass equation is given by

$$\nabla \cdot (\rho_f U) = 0 \tag{1}$$

The simplified steady-state Navier-Stokes equation:

$$(\nabla \cdot U)\rho_f U - \mu_{eff} \nabla^2 U + \nabla P - \nabla \cdot (\mu_{eff} \nabla U)^T = 0 \tag{2}$$