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The effect of fin oscillation in heat transfer enhancement in separated flow over a backward facing step

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ABSTRACT

Two-dimensional laminar fluid flow and heat transfer characteristics have been investigated numerically for a oscillating fin mounted on the top wall of backward facing step with constant bottom wall temperature. OpenFOAM is used to solve the governing equation of mass, momentum and energy conservation with the appropriate boundary conditions. Air is used as a working fluid with constant thermo-physical property ($Pr = 0.71$). It is found that the oscillating fin is the most effective method with highest average Nusselt number and lowest pressure drop, to enhance the mixing and heat transfer when it is compared to the different types of stationary fin arrangement. Further, the effect of frequency (which is directly proportional to the amplitude of velocity) and oscillation have been investigated and found that the average Nusselt number increases with the increase in velocity amplitude. It is also observed that the change in average Nusselt number is negligible with the increase in the amplitude of oscillation for a constant velocity amplitude. A correlation is also presented to express the effectiveness of the fin (η_f) in terms of ratio (K_v) of velocity amplitude (V_o) to the flow velocity (U_f) and is observed to follow the power law with constant exponent as $\eta_f = c\,K_v^{0.3}$.

1. Introduction

Flow separation is a fundamental topic in fluid dynamics and it is not preferable in some applications such as high performance heat transfer devices because of poor heat transfer in separated region, in aerospace applications because of increase in drag force, while it is preferable in combustion applications because it stabilizes the flame. The sudden expanding channels i.e., Backward facing step is the simplest geometry to study all the complex features of separated flows. This is the reason, separated flow over a backward facing step has been studied extensively in the literature because of wide range of engineering applications.

In the experiments for expansion ratio, $ER = 1.9423$ and aspect ratio, $AR = 35$, it is seen that flow separates at the step because of sudden change in streamwise velocity, forms a primary recirculation vortex and attaches in the downstream direction on the bottom wall at primary reattachment point (X_r). The length of primary recirculation vortex (X_r) increases non-linearly with an increase in Reynolds number (Re) in laminar region for $Re \leqslant 1200$, decreases irregularly in the range of transition region for $1200 < Re < 6600$ and remains constant in turbulent region for $Re \geqslant 6600$. Two-dimensional numerical simulations predicted X_r accurately for $Re \leqslant 400$ and starts showing deviation for $Re > 400$. The reason for the deviation is believed that the flow is three-dimensional in nature for $Re > 400$ [1]. Three dimensional numerical simulations predicted the 3D nature of flow and the X_r matches accurately for $100 \leqslant Re \leqslant 800$. Further, the spanwise variation of X_r also agreed well with the experiments [2]. The detailed comparison of 2D, 3D numerical simulations and experimental results showed that 2D simulation is sufficient to capture all the complex features of separated flow over a backward facing step for $Re < 400$, but 3D simulation is required to capture three-dimensional nature of the flow for $Re > 400$ [3]. A secondary recirculation vortex observed for $Re > 400$ and its size increases with increase in Reynolds number [1]. The 2D steady flow starts showing 3D unsteady characteristics for $Re \geqslant 700$ and the 3D nature of flow occurs only in particular regions of the flow, specifically at the boundaries between the two recirculation zone and main flow [4,5]. Investigation of aspect ratio variation revealed that 2D flow can be achieved even for high Reynolds number flows at the mid-span of backward facing step if appropriate aspect ratio is considered and it is reported that the results of 3D simulation of $Re = 800$ with $AR = 100$ matches well with the 2D simulation [6].

The global development causes increase in demand of energy day by day, but at the same time growing environmental pollution

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Nomenclature

Latin symbols

a	amplitude of oscillation of fin, m
AR	aspect ratio, W/h_u
d	location of fin from the step, m
ER	expansion ratio, H/h_u
H	downstream channel height, m
h_u	upstream channel height, m
$h_{x,t}$	heat transfer coefficient, W m^{-2} K^{-1}
K_v	velocity ratio, V_0/U_b
L_d	downstream channel length, m
l_f	fin height, m
L_u	upstream channel length, m
Nu_a	average Nusselt number, $\frac{1}{L_d}\int_0^{L_d} Nu_x\,dx$
Nu_x	local Nusselt number, $\frac{1}{T}\int_0^{T} Nu_{t,x}\,dt$
$Nu_{t,x}$	Nusselt number, $\frac{h_{t,x}h_u}{K} = -\left(\frac{\partial\theta}{\partial\eta}\right)_{t,x}$
Re	Reynolds number based on bulk velocity & and hydraulic diameter, $\frac{u_b(2h_u)}{\nu}$
T_c, T_h	cold and hot temperature, K
u, v	streamwise (x) and transverse (y) velocity, m/s
u_b	bulk or average velocity, m/s
V_o	velocity amplitude of oscillation of fin, m/s
W	spanwise width in 3D, m
X_o, X_f	extreme points of oscillation, m
X_r	location of primary reattachment point, m

Non-dimensional variables

$[A, D, L_f, S, X, Y] = [a, d, l_f, s, x, y]/h_u$
$[U, V] = [u, v]/u_b$

Superscripts

w	without fin case

Greek symbols

η	normal unit vector to the surface
ν	kinematic viscosity, Pa s
τ	wall shear stress, $\mu\frac{\partial u}{\partial y}$, N m^{-2}
θ	non-dimensional temp. $\frac{T-T_c}{T_h-T_c}$
κ	fluid thermal conductivity, W m^{-2} K^{-1}

necessitates to become more energy efficient. The flow separation appears in a wide range of heat transfer applications such as high performance heat exchangers, cooling of nuclear reactors, cooling passage in turbine blades, cooling system of electronic equipments, combustion chambers etc and causes poor heat transfer performance in that region. It motivates to study the enhancement of heat transfer in separated laminar and turbulent flows and the primary objective is to enhance the heat transfer in separated regions. The distribution of temperature is measured and it is observed that presence of recirculation region causes high heat transfer near X_r [7,8]. The extent of heat transfer can be quantified in terms of Nusselt number. The distribution of local Nusselt number (Nu_x) revealed that Nu_x decreases behind the step with an increase in Re because of increase in strength of primary vortex and causes poor heat transfer near the step. In the downstream, it attains peak of Nu_x and its value increases with increase in Re. Further downstream in fully developed thermal region, Nu_x is independent of Re [9]. The comparison of maximum local Nusselt number location (X_m) and reattachment point (X_r) showed that it is a special case that X_m coincides with the X_r. The X_m may be on either side of X_r depending on the magnitude of streamwise velocity and the direction of transverse velocity in the wall adjacent flow [10]. Further investigation confirmed that X_m does not necessarily locate exactly at or even close to the reattachment point [11]. The comparison of 2D and 3D simulations found that the average Nusselt number for 2D case is higher as compared to 3D case because of side wall effect. But, in case of 3D simulations a minimum aspect ratio ($AR = 16$ for $Re = 500$, when $ER = 2$ is reported) is required to achieve two-dimensional thermal behavior at the midspan [12,13]. Therefore, it is believed that 2D numerical simulations can be used to capture all the flow and thermal features at the midspan of backward facing step for $Re \leqslant 400$.

Many active and passive techniques have been proposed to enhance heat transfer in thermal transportation devices. Among these, one method is to generate vortex by installation of fins, baffles, ribs and obstacles in the flow field. increases mixing in the flow and causes enhancement of heat transfer in the channel [14,15]. In the study of forced convective heat transfer over a backward facing step with constant wall heat flux, installation of baffle or fin on the top wall causes enhancement of heat transfer. It is reported that baffle located at $D = 0.4$ from the step, is the most optimum location of fin for maximizing heat transfer and minimizing primary recirculation zone [16]. Comparison of solid and slotted baffle indicated that slotted baffle causes less pressure drop as compared to solid baffle at the expense of the decrease in average Nusselt number [17]. The inspection of three-dimensional effect found that maximum Nusselt number develops near the side walls and its location moves downstream as fin location moves in the downstream direction [18]. The investigation of nanoparticles found that the Nusselt number increases as the volume fraction of the nanoparticles and the Reynolds number increases, while it decreases as the diameter of nanoparticles increases [19]. Cheng [17] studied forced convection and Heshmati [20] mixed convection, they considered the inclined fin ($\alpha = -45^\circ$) located at $D = 0.2$ and 1 and compared the result with the vertically orientated fin. They did not find any appreciable change in flow structure except reduction in the size of primary recirculation zone. But, they observed increment in maximum Nusselt number with the inclined fin.

The constant wall temperature boundary condition is very important in some convective heat transfer processes, where phase change takes place such as condensation [21] and boiling (Vapotron effect [22]) in heat exchangers, chemical, and biological system, etc. Selimefendigil et al. [23] investigated the effect of fin height, located at $D = 1$ and compared the steady state inflow condition with the pulsating inflow condition with constant higher wall temperature. They found that Nusselt number increases with increase of fin height and Reynolds number, but the addition of a fin is not advantageous for heat transfer in unsteady flow. Kumar et al. [24] studied the effect of fin location and orientation and found that when the fin is located vertically at just above the step causes maximum heat transfer. Lorenzini et al. [25–28] studied the effect of fin shapes (I, Y and T) and compared the heat transfer resistance and pressure drop. They found that optimized Y shape offer better perspective as compare to I and T shape. Boruah et al. [29] studied the effect of shape of the baffle on hydrodynamics and entropy generation in mixed convection. They found that the average Nusselt is maximum for square baffle and entropy generation is minimum for the elliptical baffle.

To the author's best knowledge, no study has reported the study of oscillating fin in backward facing step channel. The objective of the present study is to explore the advance method of heat transfer