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Hydrothermal performance and entropy generation analysis for mixed convective flows over a backward facing step channel with baffle

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ABSTRACT

In this work, we numerically investigate the thermo-hydraulic characteristics and entropy generation for mixed convective flow through a backward facing step channel with baffle. The effect of baffle geometry is studied by considering three different shapes for the baffle viz. square, triangular and elliptical and two different baffle sizes viz. $h_b \times w_b = 1 \times 1$ and $h_b \times w_b = 2 \times 2$ designated as B1 and B2 configuration respectively. Parametric studies are also carried out to analyse the effects of baffle to step obstruction distance, number of baffles and arrangement of baffles in inline and staggered order on the fluid flow, heat transfer and entropy generation characteristics. Local and average Nusselt number, pressure drop and entropy generation are computed for all the configurations at a fixed Reynolds number $Re = 100$ and for a range of Richardson number $Ri = 0.1–1$. Our study reveals that the reattachment length decreases with the addition of the baffle inside the channel and the length is inversely proportional to the size of the baffle. Peaks of local Nusselt number are observed in the region near the baffle and the magnitude of these peaks are dependent on the baffle shape and size. It is observed that local entropy generation is minimum within the re-circulation zone while the same is maximum at the reattachment point. The larger the distance of baffle from step, the smaller is the total irreversibility associated with it and its magnitude is the least in case of elliptical baffle for both the configurations. For any baffle shape having B1 configuration, the average Nusselt number, the average pressure drop and the total entropy generation are minimum for two baffles both mounted on the top wall, while these parameters predict an increasing trend with increasing number of baffles for B2 configuration. In case of pair of baffles mounted both on the top and bottom walls, inline arrangement of baffles always incur higher heat transfer performance, pressure drop penalty and entropy generation as compared to staggered arrangement. For all the number of pairs of baffles in staggered arrangement, elliptical baffles always provide the highest heat transfer performance, least pressure drop penalty and least entropy generation among all the baffle geometries and as such in staggered arrangement, elliptical baffles in backward facing step channel is an optimum design choice from the perspective of both the thermo-hydraulic performance and entropy generation.

1. Introduction

In the field of thermo-fluidics, the phenomena of flow separation and reattachment due to recirculation and its impact on the transport characteristics have been a fundamental topic of research interest from the past few decades because of its widespread engineering applications such as combustors, heat exchangers, diffusers, turbines and many others of the kind. Although several geometrical configurations can be employed to generate such separated flows, the simplest geometry to create flows with recirculation is a channel with sudden expansion, popularly called as the backward facing step channel. Because of its geometrical simplicity and widespread usage, the study of transport phenomena through backward facing step channel has been a trending research topic.

Flow and heat transfer analysis in the laminar [1–3], transitional [4] and turbulent [5,6] flow regimes for both steady [1] and transient [7] cases have been studied for the backward facing step channel. The channel is credited with higher heat transfer capability, although it encounters pressure drop penalty. Soong and Hsueh [1] analysed the effect of cold fluid injection on laminar mixed convective flow of air through a backward facing step channel and observed that the injection of cold fluid augments the heat transfer rate on the step wall and reduces slightly on the bottom

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Nomenclature

b	dimensionless distance of baffle from step (=B/S)
B	dimensional distance of baffle from step, m
b_c	dimensionless baffle to step obstruction distance (=B_c/S)
B_c	dimensional baffle to step obstruction distance, m
Be	Bejan number
b_i	dimensionless distance between two consecutive pairs of baffles in inline arrangement (=B_i/S)
B_i	dimensional distance between two consecutive pairs of baffles in inline arrangement, m
b_s	dimensionless distance between two consecutive pairs of baffles in staggered arrangement (=B_s/S)
B_s	dimensional distance between two consecutive pairs of baffles in staggered arrangement, m
C_p	specific heat capacity, J/kg K
d	dimensionless height of the channel (=D/S)
D	dimensional height of the channel, m
E	expansion ratio (=D/(D − S))
g	acceleration due to gravity, m/s^2
Gr	Grashof number
h	heat transfer coefficient, W/m^2 K
h_b	dimensionless height of baffle (=H_b/S)
H_b	dimensional height of baffle, m
K	thermal conductivity, W/mK
l_1	dimensionless pre-expansion length (=L_1/S)
l_2	dimensionless post-expansion length (=L_2/S)
L_1	dimensional pre-expansion length, m
L_2	dimensional post-expansion length, m
L	total length of channel (=L_1 + L_2), m
n	Iteration number
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
$N_{Thermal}$	dimensionless thermal entropy generation
$N_{Viscous}$	dimensionless viscous entropy generation
N_{Total}	dimensionless total entropy generation
p	dimensionless pressure $(= P/\rho U_0^2)$
P	dimensional pressure, Pa
Pr	Prandtl number
Re	Reynolds number
Ri	Richardson number
S	dimensional step height, m
T	temperature, K
U	velocity along x-direction, m/s
v	dimensional velocity vector
V	non-dimensional velocity vector
x, y	cartesian coordinates in dimensional form
X, Y	cartesian coordinates in non-dimensional form
w_b	dimensionless width of baffle (=W_b/S)
W_b	dimensional width of baffle, m

Greek symbols

ρ	density, kg/m^3
μ	dynamic viscosity, Pa s
θ	dimensionless temperature $(= (T - T_0)/(T_H - T_0))$
β	thermal expansion coefficient
ϕ	transport variable
ν	kinematic viscosity, m^2/s

Subscripts

0	inlet condition
H	heated wall
out	outlet condition

heated wall. They also concluded that the buoyancy effect is dominant outside the recirculation zone while it is not favorable within the circulation region. Avancha and Pletcher [6] investigated for turbulent flow of air through a backward facing step channel and concluded that the rate of heat transfer is critically influenced by the viscous sub-layer.

Several researchers have also varied the orientation of the channel from horizontal [8] to inclined [9] and also vertical [10] to analyse its effect on the flow and heat transfer. Iwai et al. [9] carried out numerical investigation on the effect of pitch angle and rolling angle of backward facing step duct on the flow and thermal fields and these effects were found to be significant. The basic areas of convective study viz., natural [11], forced [12] and mixed convection [1–3,7–10] have also been studied in such a suddenly expanded channel. After numerous experimental and numerical investigations, the backward facing step channel has been used as an appropriate geometry to enhance the heat transfer rate although it encounters measurable pressure drop penalty. Abu-Mulaweh et al. [11] experimentally found that the step height of a suddenly expanded channel has significant effects on natural convection heat transfer. Saldana et al. [8] numerically studied the mixed convective flow through a 3-D backward facing step channel and found that the size of the recirculation zone both in the streamwise and transverse directions decreases with increase in Richardson number (*Ri*).

Recent studies reveal that a few investigations have also been carried out to augment the heat transfer in a backward facing step channel by using certain passive modification techniques such as incorporation of baffles (rectangular, slotted and inclined) [13,14] or by employing nanofluids [12] as coolant. Nie et al. [13] found that a baffle mounted on the top surface of a backward facing step channel increases the magnitude of the maximum Nusselt number at the stepped wall. Thereafter, Heshmati et al. [14] concluded that a slotted baffle can provide an optimal heat transfer performance with minimal pressure drop. They also used nanofluids to have further increment in heat transfer than air or water as coolant. Numerical investigations for different nanoparticles were also carried out by Al-aswadi et al. [12]. They concluded that the size of recirculation region and reattachment length can be increased by using the nanofluids with low density particles because of highly induced velocity. It can be highlighted in this context that previous studies have only depicted the flow and heat transfer characteristics for rectangular shaped baffle. It is quite obvious that the geometry of the baffle has a significant influence on the flow and heat transfer rate. However, to the best of authors' knowledge, no work has been reported on the hydrothermal analysis of mixed convective flow through a backward facing step with baffle.

Since the finite temperature difference is the driving potential for the transport of thermal energy, all heat transfer processes are irreversible in nature, thus generating irreversibility in the thermal system. Therefore, the hydrothermal performance of a thermal system alone cannot give a clear picture of the most efficient geometry, entropy generation analysis and its minimization is also required in this context. A review of the literatures related to entropy generation analysis in backward facing step channel is very limited. Abu-Nada [15] numerically studied the effect of expansion ratio of a backward facing step channel on entropy generation. They found that the Bejan number (Be) increases with