Chapter 11

Heat Transfer and Nanofluid Flow Through Different Geometries

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Additional information is available at the end of the chapter

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1. Introduction

The use of annular passages in application engineering extends through such areas as heat exchangers, gas turbines, cooling of nuclear reactor and some operation industries, cementing operations, formation fracturing, and flow of lubricants in journal bearing and pressure bushings, as well as those applications found in the form of horizontal or vertical directions. Therefore, many researchers have studied fluid flow and heat transfer in annular passages in horizontal and vertical directions for different types of fluid used in varied applications. Thus, investigations that deal with different fluids, for example air, water, oil, gas, etc., are included in this study. Regarding annular passages, there are two types; in concentric annular passages, the position of the inner pipe is in the center of the outer pipe/passage, and in eccentric annular, the position of the inner pipe is not in the center of the outer passage.

Enhancement of heat transfer has been widely researched with different techniques in the last decades. Most researchers have studied the effect of changing the feature of geometry on heat transfer rate. The flow through an axisymmetric sudden expansion or contraction, over backward-facing or forward-facing steps and through ribbed channels, creates separation flow.

There are many experimental and numerical studies that have investigated the effect of separation flow on performance of heat transfer, using different configurations and boundary conditions. Most of these investigations were carried out for separation air flow, while a few were carried out for separation liquid flow in sudden expansion. In the last decade, researchers have used nanofluid in their studies to improve augmentation of heat transfer. Studies on heat transfer to nanofluid flow in sudden expansion, or over backward-facing and forward-facing steps, are very limited for the laminar range, and most have been numerical, the turbulent range of nanofluid flow has not yet been investigated. The main efforts toward studying separation flow were carried out in the late 1950s. All of these efforts were performed experimentally using many flow visualization techniques, and they deal exclusively with turbulent or laminar flows. This chapter covers most of the investigations that have studied heat transfer and pressure drop of separation flow with fluid and nanofluid, in sudden expansion and backward-facing and forward-facing steps, as well as heat transfer and flow in annular pipes.

2. Nanofluid

Nanofluid is a mix of a base fluid and nanometer-sized particles called nanoparticles. The base fluid is commonly water, oil, and ethylene glycol, while there are different types of nanoparticles, including metals, carbides, oxides, and carbon nanotubes. There are several parameters that affect the performance of nanofluid, including the size and shape of the nanoparticles, concentration, base fluid, and if the nanoparticle type is metal or non-metal. For example, nanoparticle size has a significant impact on thermal conductivity; the small size of the nanoparticle leads to an increase in surface area, and therefore researchers have employed different types of nanofluids in different geometries to reach augmentation of heat transfer.

Nanofluid can be prepared by two methods. In summary, the first method creates nanoparticles with chemical or physical processes (e.g., evaporation and inert-gas condensation processing), and then disperses them into a host fluid. The second method includes production and dispersal of the nanoparticles directly into a host fluid.

3. Annular pipe

Earlier studies, which focused on forced, natural and mixed heat transfer to fluid flow in an annular passage, were carried out by Taylor [1], Dufinescz and Marcus [2], Zerban [3], Foust and Christian [4], Jakob and Rees [5], TEMA [6], Monrad and Pelton [7], Davis [8], Lorenzo and Anderson [9], Chen et al. [10], McMillan and Larson [11], Carpenter et al. [12], Bailey [13], Migushiva [14], Trefethen [15], MacLeod [16], Barrow [17], and Murakawa [18, 19]. They adopted numerical and experimental forms that investigated forced, natural and mixed heat transfer to fluid flow with vertical or horizontal annular passages and rotating or non-rotating flow for different boundary conditions, such as uniform heat flux or uniform temperature wall, for either inner pipe or outer pipe or both. They also used various types of fluids in their studies. These studies have generated various results, including the effects of the step ratio between the inner pipe and outer pipes, eccentricity, roughness of surfaces, type of fluid, and velocity of fluid in an annular passage on the heat transfer processes; in addition, the temperature profiles of fully developed flow, thermal stresses and thermal length in earlier studies also contributed to good understanding of these aspects.

Miller et al. [20] studied turbulent heat transfer to water flowing in an annulus with a heated inner pipe. They showed the effect of the space ratio, Reynolds number and heat flux on the enhancement of heat transfer, and obtained experimental results that were 20 % higher than the calculated value obtained by using Colburn's equation for internal flow in pipes with an equivalent diameter. Quarmby and Anand [21, 22] conducted a study on turbulent heat transfer and fluid flow in a concentric annular passage with constant wall temperature and uniform heat flux. They observed that the values of the Nusselt number for boundary conditions of uniform heat flux are higher in comparison to that for boundary conditions of constant wall temperature.

Donne and Meerwald [23] have studied heat transfer and friction loss of turbulent flow of air in smooth annuli at high temperature. They measured subsonic turbulent flow of air in smooth annuli with diameter ratios of 1.99 and 1.38, with an inner pipe heated up to 1000°C. They obtained their Nusselt numbers as correlated with equation (1):

$$Nu_B = 0.018\left(\frac{D_2}{D_1}\right)^{0.16} Re_B^{0.8} Pr_B^{0.4} \left(\frac{T_w}{T_E}\right)^{-0.2} \quad (1)$$

It was observed that the work of Petukhov and Roizen [24] correlated well with equation (1) at low temperature differences ($T_W/T_E \rightarrow 1$).

Also, the average Nusselt numbers at the inner pipe of the annulus are given by equation (2).

$$Nu_B = 0.0217\ Re_B^{0.8} Pr_B^{0.4} \left(\frac{T_w}{T_E}\right)^{-0.2} \quad (2)$$

For experimental investigations, good agreement for circular tubes was obtained by Dalle Donne [25]. Dalle Donne presented experimental data with the correlating factor A= $(Nu_B / Re_B^{0.8} Pr_B^{0.4})_{TW/TB=1}$ with a ratio of diameter (D1/D2), and made comparisons with previous theories and experimental findings reported by Donne and Meerwald [23], Petukhov and Roizen [24], Wilson and Medwell [26], Kays and Leung [27], Deissler and Taylor [28], and Sheriff and Gumley [29].

Heikal and Hatton [30] presented predictions and measurements of fully developed turbulent non-axisymmetric flow and heat transfer in an annular channel by implementing the turbulence model. They showed good agreement with experimental data, especially for velocity profiles, friction factor and shear stress. They also showed best agreement between predicted and measured data when the ratio of circumferential to radial mass diffusivity of heat was maintained at a value of 2 over the whole cross section. Robinson and Walker [31] investigated to obtain the value of circumferential diffusion heat for turbulent flow in a symmetrical annular passage and compared the obtained results with theoretical solutions.

Stein and Begell [32] carried out investigations on turbulent water flow and heat transfer in internally heated annuli by implemented cosine and uniform lengthwise heat flux distributions. They computed 900 evaluates of local heat transfer coefficients of water flow with heated inner pipe. They observed no considerable effect of cosine heat flux distribution on the heat transfer coefficients. Chen and Yu [33] also studied turbulent heat transfer to flowing liquid metals in concentric annular channels. They focused on the effect of variable heat flux and entrance region dimensions on the Nusselt number, and showed that the predicted Nusselt number agreed with the experimental value. Lee et al. [34] presented numerical results of heat transfer in fully developed flow by using the K-ε equation model in annular pipes with rectangular roughness. They obtained more improvement in the Nusselt number by using a curvature correlation model in comparison to the standard K-ε equation model. They also obtained a maximum value for the Nusselt number at the near reattachment point of the separated flow. The computational results have shown good agreement with previous investigations reported by Kang and Choi [35], Lee [36], and Hong et al. [37].

Ho and Lin [38] numerically investigated heat transfer to air–water flow in horizontal concentric and eccentric cylindrical annuli with constant heat flux at the outer wall and isothermal condition at the inner one. They observed that an increase of heat exchange transfer to air–water interface occurred at mixed boundary conditions. Ahn and Kim [39] performed an analytical and experimental study of heat transfer and fully developed fluid flow in rough annuli by using artificial roughness elements on the wall of the inner pipe or outer pipe or both. They obtained enhancement in the heat transfer coefficient due to the effect of the roughness element on turbulence enhancement.

Shahi et al. [40] performed a numerical study on natural convection heat transfer rate in vertical annular channels with nanofluid copper-water. By using a finite volume method with Fortran, the analysis of equations showed an increase in Nusselt number with the increase of solid concentration of nanofluid, and the maximum Nusselt number occurred as inclined angle of the annular channel was equal to zero degree. They validated their result by comparing values of the Nusselt number with Guj and Stella [41] and Davis and Thomas [42].

Mehrizi et al. [43] have numerically studied natural convection heat transfer to Copper (Cu)-water nanofluid flow in horizontal cylinder annuli with an inner triangular cylinder, using the Lattice Boltzmann method. They showed increased enhancement of heat transfer and stream functions with an increase in the volume fraction of nanoparticles and with the inner cylinder moving downward, while there was a decrease in the improvement of heat transfer with the inner cylinder moving horizontally. In contrast, Matin and Pop [44] presented a numerical study of the natural heat transfer to Cu-water nanofluid flow in a horizontal, eccentric annulus. They applied stream function vorticity formulation in the polar coordinate in order to obtain highly accurate results on the effect of eccentric and volume friction of nanoparticles on the Prandtl number and the Nusselt number, and obtained good agreement with previous investigations. The enhancement of heat transfer for two-phase mixed convection of laminar AL_2O_3 nanofluid flow in an annulus with constant heat flux was numerically studied by Mokhtari et al. [45]. In their simulation, a three-dimensional finite volume method was used and the Brownian motions of nanoparticles were considered to calculate the effects of thermal conductivity and dynamic viscosity. The computational data indicated that the Nusselt number increased with an increase in the volume fraction of nanoparticles, but the friction factor was not affected.

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4. Sudden expansion

The earliest investigations of flow in sudden expansion were carried out by Macango and Hung [46]. They obtained results that presented the streamlines and vorticity contour as functions of the Reynolds number. Also, they analyzed the dynamic interaction found between the main flow and captive eddy.

Durst et al. [47] have experimentally studied the flow visualization and laser–anemometry measurements of flow at the downstream of a plan 3:1 symmetric expansion in a duct with an aspect ratio of 9.2:1. The flow was found to be markedly dependent on Reynolds number, as strongly noticed in a three-dimensional study at well away from the channel corners at the lowest measurable velocities. The separation regions behind each step were of equal length at a Reynolds number of 56, which indicated that the symmetric velocity profiles existed from the expansion to a fully developed parabolic profile for the downstream, although there were substantial three-dimensional effects in the vicinity of the separation regions. Study of the velocity profiles shows good agreement with those obtained by solving the two-dimensional momentum equation. The data indicated that the two separation regions were of different lengths, leading to asymmetric velocity profiles at the Reynolds number of 114, whereas at the Reynolds number of 252, the third separation zone was found on one wall, downstream of the smaller of the two separation zones adjacent to the steps.

Afshin and Peter [48] have experimentally studied laminar water flow through confined annular channel with sudden expansion. They used particle image velocimetry (PIV) and refractive index matching (RIM) to measure velocity and length of separation, where they showed increase separation regions with increase of Reynolds number, and as shown in Figs. 1–3, they also obtained good agreement with the numerical result reported by Nag and Datta [49].

Guo et al. [50] conducted a numerical study on the effect of heating on corner recirculation zone (CRZ) in sudden expansion with gas flow. They noticed a decrease in the length of the corner recirculation zone as the heating gas flow increased in sudden expansion. Oliverira and Pinho [51] conducted a numerical study of pressure drop coefficient of laminar Newtonian flow through sudden expansion by using a finite volume method based on a second order differencing scheme. The numerical results indicate a decrease of local loss coefficient with an increase of (between 1 and 225 in the) Reynolds number, and it was also found that a correlation for local loss coefficient could be represented by equation 3.

$$C_I = \frac{19.2}{Re^{0.93}} - 2.55 + 2.87 \log Re - 0.542 \left(\log Re\right)^2 \tag{3}$$

Chiang et al. [52] conducted a computational investigation on the effect of side wall on structure laminar incompressible fluid flow over a plane symmetric sudden expansion. In their analysis, 14 aspect ratios were used and were varied from 3 to 48, with Re = 60 for three-dimensional analysis and Re = 60 and 140 for two-dimensional analysis. The numerical results

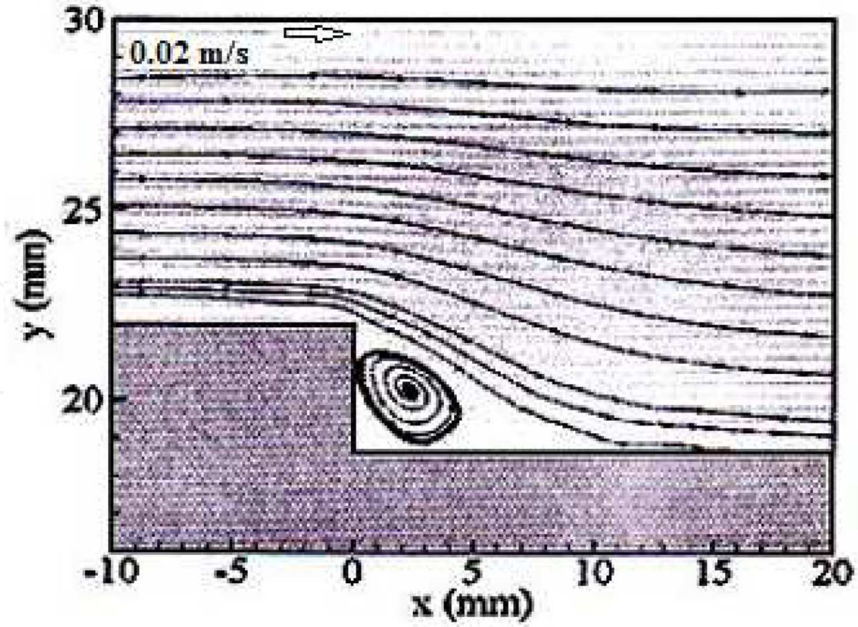

Figure 1. Measurements of velocity flow field at Re= 100.

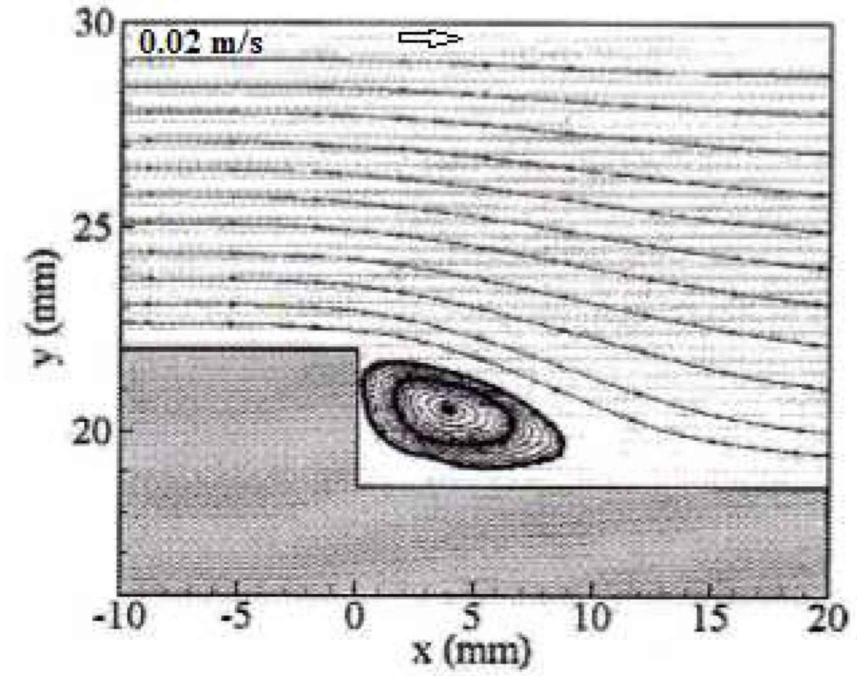

Figure 2. Measurements of velocity flow field at Re= 300.

were in good agreement with the experimental results of Fearn et al. [53], whose experimental results indicated that symmetric flow occurred at Re = 26, while asymmetric flow happened at Re values up to 36. Oliveira has reported numerical simulations on viscoelastic liquid flow in symmetric sudden expansion [54]. The constitutive model follows FENE-MCR, employed in this simulation as three meshes with different sized cells, a Reynolds number ranging from

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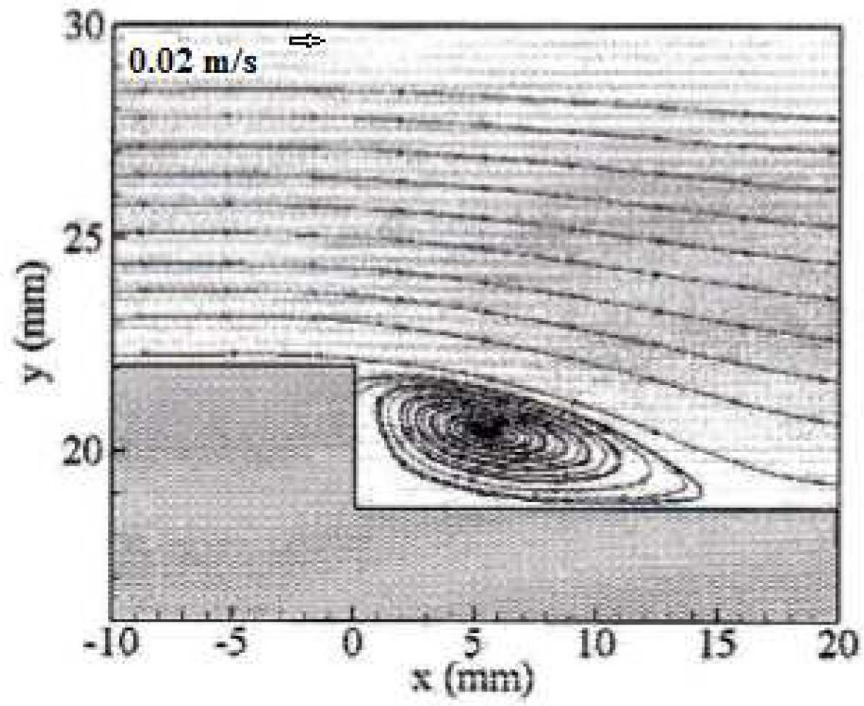

Figure 3. Measurements of velocity flow field at Re= 500.

0 to 100 and an expansion ratio of 1:3. Due to asymmetric vortex shapes, a pitch-fork type bifurcation takes place beyond the critical Reynolds number (Rec = 64), while it occurred at Rec=54 with Newtonian fluid in the same expansion ratio. Hammad et al. [55] performed a numerical study of the laminar flow of non-Newtonian Herschel Bulkley fluid through axisymmetric sudden expansion. They used a finite difference method to solve governing fully elliptic momentum and continuity equations, and obtained the regime of laminar flow for a range of yield numbers, Reynolds number, and power–law index values, where the range of Re varied between 50 and 200, yielded numbers that varied between 0 and 2, and power-law index values varied between 0.6 and 1.2. They obtained significant dependence of the flow for large values of yield number only, while at lower yield number, the power law index value became effective with yield number on the flow field. They also found good agreement with Hammad [56] and available experimental results for reattachment length. Meanwhile, Miranda et al. [57] numerically studied the local loss coefficient for inelastic laminar fluids flow in axisymmetric sudden expansion by using the finite volume method, and the sudden expansion varied from 1 to 2.6. The authors showed that the local loss coefficient varied inversely with Reynolds number at low Re.

Numerous studies have adopted various models for analysis of heat transfer in separated flow with sudden expansion, and compared the obtained results with experimental data or with other numerical results. Cheing and Launder [58] performed a numerical study of turbulent heat transfer and flow in a separation region with an abrupt pipe expansion by using the standard k-ε model, and thus obtained good agreement with the experimental data of Zemanick and Dougall [59].

Gooray et al. [60] presented numerical calculations for heat transfer in recirculation flow over two-dimensional, rearward-facing steps and sudden pipe expansions by using the standard k-∈ model and low-Reynolds number k-∈ model. The Reynolds number ranged from 500-10,000 in the investigation. The authors applied two-dimensional back-step and pipe expansion geometries for numerical turbulent flow modeling, and compared the results with the experimental data of Zemanick and Dougall [50], Aung and Goldstein [61], and Sparrow and O'Brien [62]. The investigations considered herein have confirmed that the improved k-∈ procedure is capable of providing an insight into complex phenomena having turbulent separated and reattachment flow with heat transfer.

The study of laminar nanofluid flow in sudden expansion is very limited and appears only in Santosh Christopher et al. [63], in a preformed numerical study on laminar Al_2O_3, Ag, Cu, SiO_2, and CuO nanofluid flow in sudden expansion. They used the same method as Kanna and Das [64] to solve sudden expansion flow and backward-facing flow with Reynolds numbers from 30 to 150 and volume fractions of 0.1, 0.2, and 0.5. The results showed a decrease in reattachment length of about 1.3% compared with the values obtained by Eiyad Abu-Nada [65], as shown in Fig. 4.

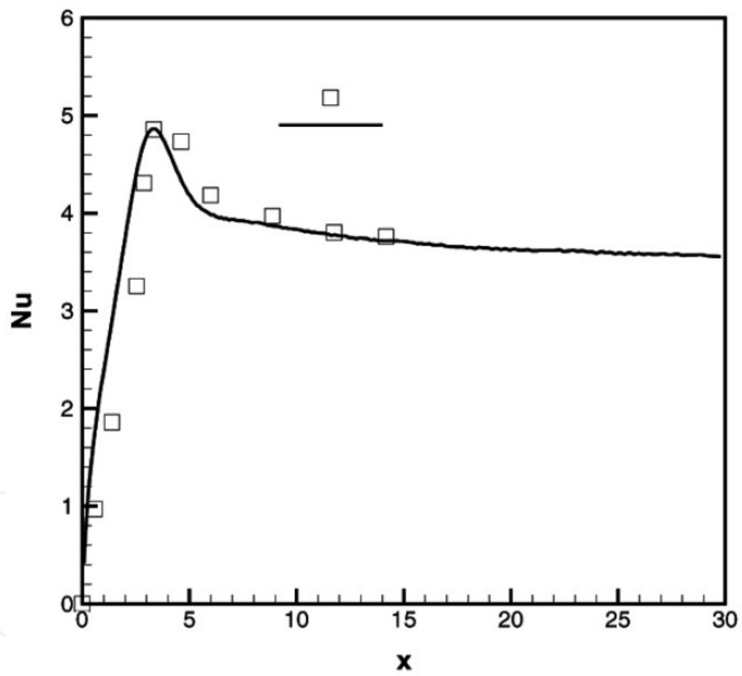

Figure 4. Comparison of Nusselt number for SiO2 at Re = 100.

5. Backward-facing step

Armaly et al. [66] conducted experimental and theoretical experiments on the two-dimensional effect of the Reynolds number on reattachment length flow downstream of a backward-facing step in a rectangular channel using laser Doppler measurement where the range of Reynolds number varied between 70 and 8000 and the aspect ratio was 1:36. The experimental result obtained agrees with data predicting increasing reattachment length with increasing Reynolds number.

Barton [67] used a particle phase model with Eulerian-Lagrangian to study laminar flows over backward-facing steps with a stream of hot particles. He focused his investigation on the effect of heat transfer and thermal characteristics on recirculation regions, and noticed that the streamlines in the separation region were ten times smaller than the streamlines in the free flow.

Lee and Matteescu [68] conducted an experimental and numerical study on two-dimensional air flows over a backward-facing step. They measured lengths of separation and reattachment on lower and upper duct by using a hot wire probe with an expansion ratio of 1.17 and 2 and Re below 3000. The numerical and experimental results agree with previous experimental data for separation and reattachment lengths and locations on the lower and upper wall of the duct.

Armaly et al. [69] adopted experimental measurements of velocity in three-dimensional laminar separated flows on backward-facing steps by using two components: laser Doppler velocimeter where the expansion ratio is 2.02, and Reynolds number ranging from 98.5 to 525. They showed an increase in the size of recirculation regions with increased Reynolds number, and the maximum location of the stream-wise velocity line component (u) is zero at the stepped wall with constant Reynolds number at the sidewall.

Barbosa et al. [70] conducted a numerical study of three-dimensional mixed laminar air flow over a horizontal backward step using the finite volume method. The bottom wall of a channel was heated with constant temperature and the other walls were adiabatic, the aspect ratio was equal to 4 and the range of Richardson number (Ri) varied between 0 and 3. The numerical results indicated a decrease in the size of the primary recirculation region with increase in Richardson number, and also moved the maximum value of the average Nusselt number. Li and Armaly [71] presented a numerical study of laminar mixed convection in a three-dimensional backward-facing step, where the fill elliptic 3 coupled governing equation was solved using the finite volume method. They found that buoyancy force and temperature affect reattachment length.

The pioneer researchers who applied a large eddy simulation model for the analysis of turbulent heat transfer in separated flow over a backward-facing step are represented by Labbe et al. [72], Avancha and Pletcher [73], and Zouhaier et al. [74]. These researchers showed significant improvement of heat transfer rate in the recirculation zone and obtained trends of heat transfer coefficients that agreed with previous experimental data.

Numerical simulations for two-dimensional turbulent forced convection flows adjacent to backward-facing step were investigated by Chen et al. [75]. The researchers paid attention to the effects of step height on turbulent separated flow and heat transfer. They considered Reynolds number and duct height downstream from the constant step as Re0 = 28,000 and H = 0.19 m, respectively. Heat flux was uniformly maintained at qw = 270 W/m^2 at the stepped wall downstream from the step, while other adjacent walls were treated as adiabatic. The velocity and temperature fields were calculated by using two equations at low Reynolds number and turbulence models. Results of Abe et al. [76, 77] showed that with the increase of step height, the peak values of the transverse velocity component reduces as shown in Fig. 5, while the maximum temperature becomes greater as the step height increases as shown in Fig. 6. Chen et al. also reported that the bulk temperature increases more rapidly with the increase of step height.

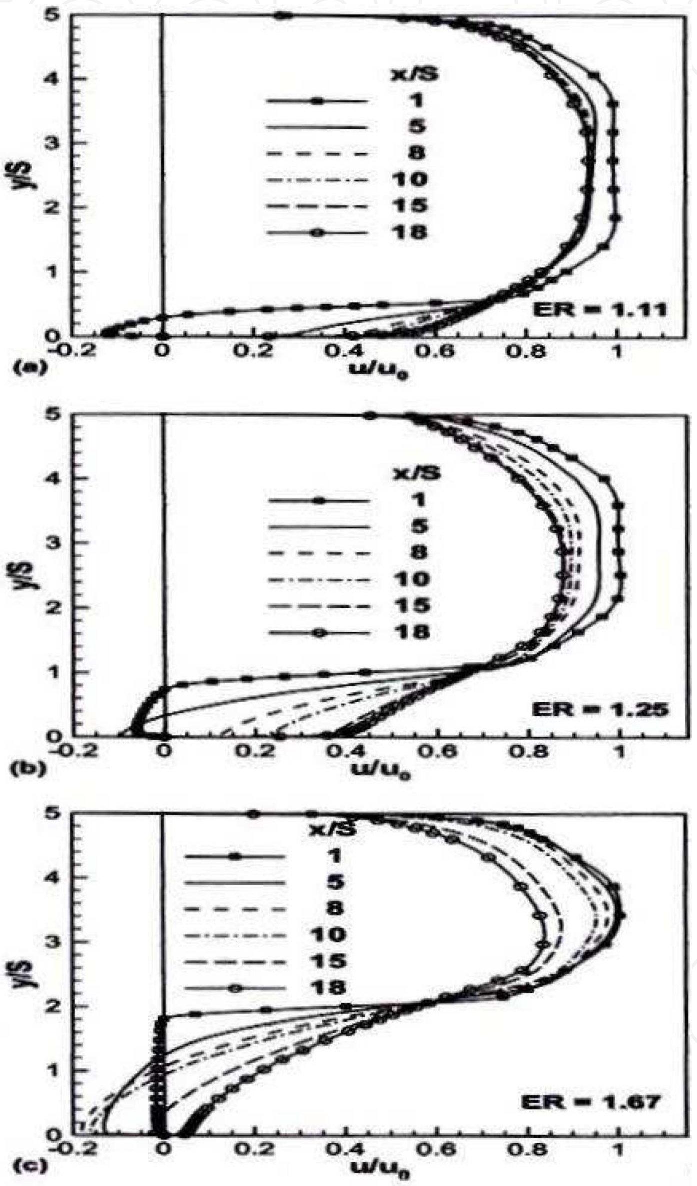

Figure 5. Distribution of the mean streamwise velocity component (u) at several x-planes.

Abu-Nada [65] can be considered a pioneer in the numerical study of heat transfer to nanofluid over a backward-facing step. The types of nanoparticles in this study are represented by Cu, Ag, Al_2o_3, Cuo, and Tio_2, with volume frictions between 0.05 and 0.2 and Reynolds numbers ranging from 200 to 600. Momentum and energy equations were solved by using the finite

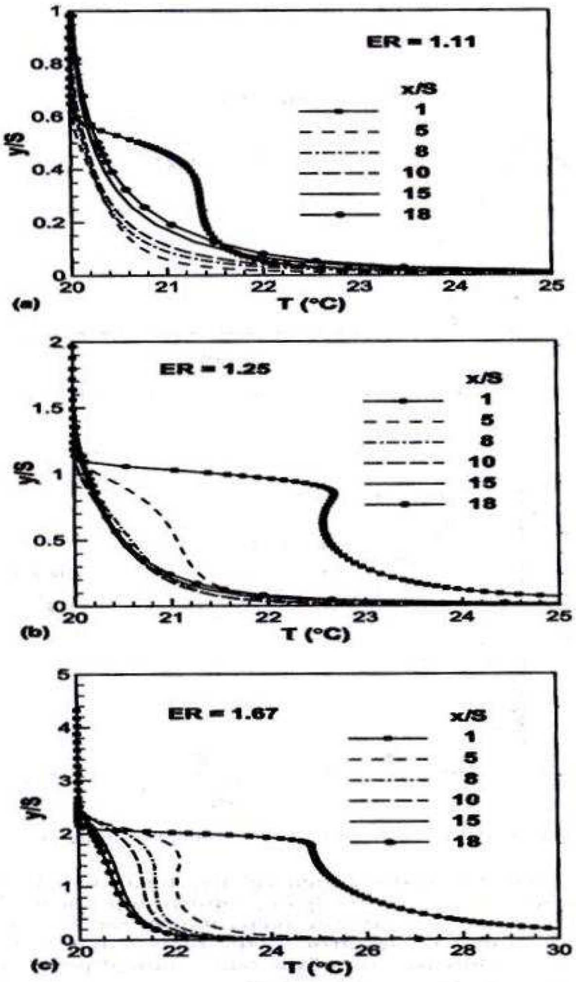

Figure 6. Distribution of the mean temperature at several x-planes.

volume method, and an increase in Nusselt number was observed at the top and bottom of the backward-facing step. Also, the investigations found high thermal conductivity of nanoparticles outside of recirculation zones. Later, Kherbeet et al. [78] presented a numerical investigation of heat transfer and laminar nanofluid flow over a micro-scale backward-facing step. The Reynolds numbers ranged from 0.01 to 0.5, nanoparticle types comprised Al_2O_3, CuO, SiO_2, and ZnO, and the expansion ratio was 2. An increasing Reynolds number and volume fraction seemed to lead to an increasing Nusselt number; the highest Nusselt number value was obtained with SiO_2.

6. Forward-facing step

Stuer et al. [79] presented an experimental study of the laminar separation flow on forward-facing steps by using particle tracking velocimetry to get more information about separation phenomena. The experimental results obtained showed an increase in distance between the breakthroughs in span at decreased Reynolds numbers, and they also noticed that the transverse direction of separation was slow compared with a short time scale.

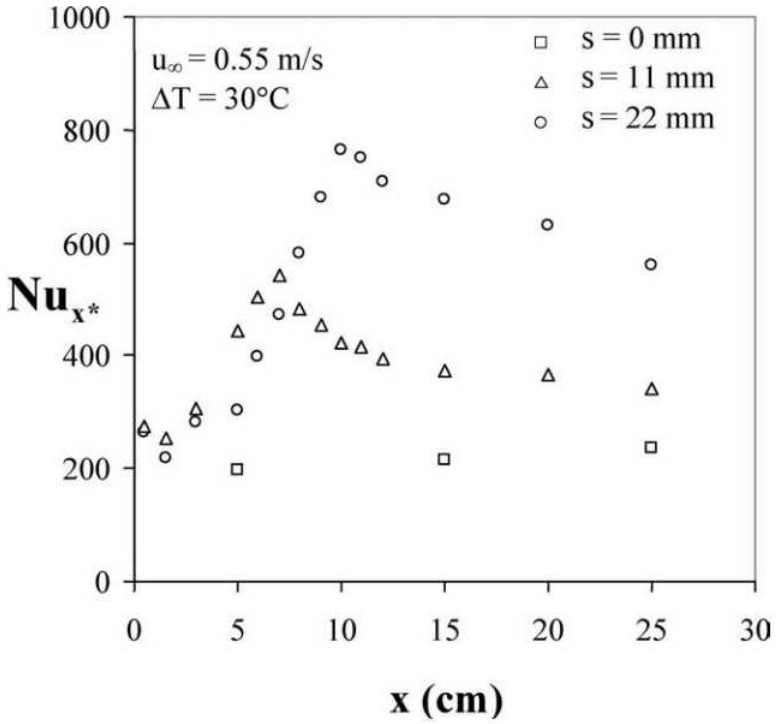

Figure 7. Local Nusselt number variation downstream of the step.

Abu-Mulawah et al. [80] have also reported on the effect of step height on turbulent mixed convection flows over a backward-facing step. Abu-Mulawah [81] noticed that the highest local Nusselt number at the reattachment region for the backward-facing and forward-facing steps in turbulent natural convection flow along a vertical flat plate.

The turbulent fluid flow and heat transfer of a mixed convection boundary-layer of air flowing over an isothermal two-dimensional, vertical forward step was experimentally investigated by Abu-Mulaweh [82]. He studied the effect of forward–facing step heights on local Nusselt number distribution, as shown in Fig. 7. The results indicate that the Nusselt number increases with the increase of step height, and the highest value is obtained at the reattachment region. The present results indicate that the increase of step height leads to an increase in the intensity of temperature fluctuations, the reattachment length transverse velocity fluctuations and the turbulence intensity of the stream.

7. Conclusion

Heat transfer and nanofluid flow through annular pipe over a backward-forward facing step has been presented in this chapter. The effect shape of geometry on thermal performance is clearly seen in experimentally and numerically studies in the literature. The results show that

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heat transfer rate increases with an increase in step height and Reynolds number. More augmentation of heat transfer was found using nanofluid, due to an increase of heat transport in the fluid. The enhanced thermal conductivity and viscosity of nanofluids, as well as the random movement of nanoparticles, effect the increased enhancement of heat transfer and stream functions. Also, using nanofluids could offer a positive effect on the energy crisis that is happening in the world.

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