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Mixed Convection in Cylinders – A Comprehensive Overview and Understanding

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ABSTRACT

: This paper gives a comprehensive overview and understanding related with mixed convection in cylinders. About one-hundred papers which are published in different local and international journals and conferences started from the past decade until the recent years are collected and described in various sections to give both researchers and readers a good overview and a solid background about mixed convection flow and heat transfer in cylinders to develop their future researches. In addition, the papers reviewed including numerical, analytical and experimental works related with mixed convection in cylinders are grouped into categories which collect papers with the same research subject. Moreover, mixed convection in horizontal , vertical and rotating cylinders subjected to a different boundary conditions as well as cylinders embedded inside a channel , annulus and cavity are described and reviewed.

KEYWORDS: Mixed convection , Cylinder , Literature review , Steady flow

1.INTRODUCTION

Mixed (free and forced) convection flow and heat transfer around cylinders has received much attention in the recent years due to its many important practical applications such as thermal design of buildings , electronics cooling , solar collectors , drilling operations , commercial refrigeration ,geothermal power generation and float glass production. During mixed free and forced convection, it is necessary to add the contributions of free and forced convection in assisting flows and to subtract them in opposing flows. Also, the mixed convection phenomena becomes very important when the forced velocity induced by a mechanical device like a fan has an effect equal to the free stream velocity induced by the buoyancy force which appears due to the density variation. Therefore, it is important to understand the heat transfer characteristics of mixed convection around cylinders. To the author knowledge , no specific review paper up to date was found in the literature which deals with the mixed convection in cylinders. Therefore, this comprehensive paper is prepared carefully to collect and describe about most one-hundred published papers in the combined free and forced convection flows in cylinders and gives both researchers and readers in this field an excellent review to prepare and improved these published papers.

2. LITERATURE REVIEW CLASSIFICATION

2.1 A cylinder of different shapes embedded inside a cavity

Mansutti et al. [1] checked the validity of using the discrete vector potential model for the mixed convection flow in a square annulus. They concluded that the existence of the internal square annulus inside the enclosure caused a secondary recirculating zone in the annulus region with lid-driven wall. **Yang** and **Farouk [2]** numerically examined the laminar mixed convection flow around a heated horizontal square cylinder rotating slowly within a concentric circular enclosure. **Rahman et al. [3]** studied numerically by employing Galerkin finite element method the combined free and forced convection in a two-dimensional square vented cavity with a uniform heat source applied on the right vertical wall. A circular heat conducting horizontal cylinder was placed somewhere within the cavity. The computations were carried out for a wide ranges of Reynolds number (Re) and the Richardson number (Ri) .The results indicated that both the heat transfer rate from the heated wall and the dimensionless temperature in the cavity were strongly depended on the size, location and thermal conductivity of the cylinder. **Rahman et al. [4]** carried out a numerical simulation by using a finite element scheme for two-dimensional steady laminar mixed convection flow in a vented cavity with a heat conducting horizontal square cylinder for different Richardson numbers varying over the range of 0.0 to 5.0. They investigated also the effect of the inner cylinder position on the fluid flow and heat transfer in the cavity. The location of the inner cylinder was changed horizontally and vertically along the cavity centerline. The results indicated that the flow field and temperature distributions inside the cavity were strongly dependent on the Richardson numbers and the inner cylinder position. **Rahman et al. [5]** performed a computational study of steady laminar mixed convection flow inside a vented square cavity with a heat conducting horizontal solid circular cylinder placed at the cavity center. Richardson number was varied from 0.0 to 5.0 and the cylinder diameter was varied from 0.0 to 0.6. It was found that the streamlines, isotherms, average Nusselt number at the heated surface, average fluid temperature in the cavity and dimensionless temperature at the cylinder center were strongly depended on the Richardson number and the cylinder diameter. **Oztop et al. [6]** studied mixed convection heat transfer in a lid-driven air flow within a square enclosure

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having a circular body. Flows were driven by the left hot lid wall which moved up or down in y-direction while the other walls were considered stationary. The cavity was differentially heated while the horizontal walls were assumed adiabatic. Three different temperature boundary conditions were applied for the inner cylinder as adiabatic, isothermal or conductive. The computation was carried out for wide ranges of Richardson numbers, inner cylinder diameter and center and location of the inner cylinder. It was found that the most effective parameter on flow and thermal fields was the moving lid orientation , while the thermal conductivity became insignificant for small values of the circular body diameter. **Rahman et al. [7]** studied numerically combined free and forced convection in a two dimensional rectangular cavity with a uniform heat source applied on the right vertical wall. A circular heat conducting horizontal cylinder was placed somewhere within the cavity. The results were presented for wide ranges of the Reynolds number (Re), Richardson number (Ri), Prandtl number (Pr) and some physical parameters. The interaction between forced airstreams and the buoyancy-driven flow by the heat source were demonstrated by the distributions of streamlines, isotherms and heat transfer coefficient. **Rahman et al. [8]** studied numerically using finite element method the mixed convection flow inside a rectangular ventilated cavity in the presence of a heat conducting square cylinder at the center. An external fluid flow enter the cavity through an opening in the left vertical wall and exits from another opening in the right vertical wall. Results were presented in the form of stream and isothermal lines , average Nusselt number of the heated wall, average temperature of the fluid in the cavity and the cylinder center temperature for the range of Richardson number and cavity aspect ratio. **Costa** and **Raimundo [9]** numerically studied mixed convection in a differentially heated square enclosure with a rotating cylinder centered within it. Depending on the cylinder rotation, the natural and forced convection effects could be combined or opposite. The influence of the cylinder through its radius, rotating velocity, thermal conductivity and thermal capacity on the resulting mixed convection problem was investigated. Results illustrated the rotating cylinder effects on the thermal performance of the enclosure. Also, it was found that the thermo-physical properties of the cylinder were important on the overall heat transfer process across the enclosure. **Rahman et al. [10]** analyzed using finite element method the mixed convection heat transfer in a square cavity with a centered heat conducting horizontal square solid cylinder. The cavity right vertical wall was kept at constant temperature while the remaining three walls were kept thermally insulated. An external flow entered the cavity through an opening in the left vertical wall and exits from another opening in the right vertical wall. They concluded that Reynolds number had a significant effect on the flow field in the pure forced convection and in the pure mixed convection region, but Prandtl number had significant effect on the flow field in the pure mixed convection and in the free convection dominated region. Also, the inlet and outlet port locations had a significant effect on the flow and thermal fields in the three convective regimes. **Mamun et al. [11]** studied the mixed convection heat transfer characteristics within a ventilated square cavity having a centered heated hollow cylinder. Flows were imposed through the inlet at the bottom of the left wall and exited at the top of the right wall of the cavity. A wide range of parameters such as Reynolds number, Richardson number, cylinder diameter and the solid-fluid thermal conductivity ratio were considered. It was observed that the cylinder diameter had a significant effect on both the flow and thermal fields but the solid-fluid thermal conductivity ratio had a significant effect on the thermal field only. **Hussain** and **Hussein [12]** investigated numerically the laminar steady mixed convection in a two-dimensional air filled square enclosure with a rotating circular cylinder of radius (R= 0.2 L) enclosed inside it. The left side wall was subjected to an isothermal temperature higher than the opposite right side wall. The upper and lower enclosure walls were considered adiabatic. Fluid flow and thermal fields and the average Nusselt number were presented for the Richardson numbers ranging as 0, 1, 5 and 10, while Reynolds number ranging as 50, 100, 200 and 300. They concluded that increase in the Richardson and Reynolds numbers had a significant role on the flow and temperature fields. Also, the rotating cylinder locations had an important effect in enhancing convection heat transfer in the square enclosure. **Saha et al. [13]** studied the effect of the centrally positioned adiabatic cylinder on the heat transfer by the laminar mixed convection in a tilted lid-driven square enclosure heated uniformly at the bottom by a constant heat flux. The results were presented for various inclination angles and Richardson numbers. They concluded that for all Richardson numbers considered in their study, the flow and thermal fields eventually reach the steady state with the symmetric shape about the vertical centerline through the inner circular cylinder center. It was also found that the cavity inclination angle was an important parameter affecting the fluid flow and heat transfer characteristics. **Billah et al. [14]** analyzed numerically using the finite element method the mixed convection heat transfer in a lid-driven cavity along with a heated circular hollow cylinder positioned at the center of the cavity . The computation was carried out for wide ranges of the Richardson numbers, cylinder diameter and solid-fluid thermal conductivity ratio. Results were presented in the form of streamlines, isothermal lines, average Nusselt number at the heated surface and fluid temperature in the cavity for the mentioned parameters. It was found that the flow field and temperature distribution strongly depended on the cylinder diameter and also the solid–fluid thermal conductivity ratio at the three convective regimes. Very recently , **Rahman et al. [15]** numerically investigated the mixed convective flow and heat transfer controlled by a heated hollow cylinder inside an open cavity attached with a horizontal channel. All the channel and cavity boundaries were perfectly insulated while the cylinder inner surface was heated uniformly by a heat flux (q). Computations had been conducted for Rayleigh number (Ra = 10^3–10^5), Prandtl number (Pr) varying from 0.7 to 7 and solid to fluid thermal conductivities ratio from 0.2 to 50. Results were presented in terms of streamlines, isotherms, average Nusselt number (Nu_{av}), drag force (D) and maximum bulk temperature (θ_{max}).

2.2 Cylinders with constant heat flux , local heating and internal heat generation.

Kaviany [16] studied numerically the laminar steady combined convection in a horizontal annulus subjected to a constant heat flux on the inner cylinder and an adiabatic outer cylinder. Numerical results were presented for Rayleigh numbers varying from 10^5 to 10^9 and Prandtl number varying as (Pr = 0.7, 7 and 70). The profiles of axial velocity and the inner surface temperature were presented and discussed. **Lee et al. [17]** studied the mixed convection problem along vertical cylinders and needles subjected to a uniform surface heat flux. **Ahmad** and **Qureshi [18]** studied numerically by using the finite difference method the laminar mixed convection of air from a uniform heat flux horizontal cylinder in a cross flow. The results were presented for a wide range of Grashof and Reynolds numbers. The mixed convection boundary-layer flow of Newtonian fluid from a horizontal circular cylinder with a constant surface heat flux was investigated numerically **by Nazar et al. [19** and **20]**.Also they solved the same problem for micropolar fluids **[21]** .They discussed the effects of mixed convection parameter and the Prandtl number on the flow and heat transfer characteristics as well as the boundary layer separation point position. **Laskowski et al. [22]** studied both experimentally and numerically the mixed convection heat transfer to and from a circular cylinder in a cross water flow with heating from below at low Reynolds number. The experiments were carried out in a high aspect ratio water channel. The test section inflow temperature and velocity, channel lower surface temperature and cylinder surface temperature were controlled to yield either laminar or turbulent flow for a desired Richardson number. Predicted and measured heat flux distributions around the cylinder were compared for values of the Richardson number varied from 0.3 to 9.3. They concluded that the predicted spatially averaged Nusselt number was from 37% to 53% larger than the measured spatially averaged Nusselt number. **Ishak [23]** investigated the steady mixed convection boundary layer flow along a vertical cylinder with prescribed surface heat flux. The free stream velocity and the surface heat flux were assumed to vary linearly with the distance from the leading edge. Both the case of the buoyancy forces assisting and opposing the development of the boundary layer were considered. Computed results were dependent on the mixed convection parameter, the curvature parameter, and the Prandtl number. It was found that the boundary layer separation was delayed for a cylinder compared to a flat plate. **Bachok** and **Ishak [24]** investigated the steady mixed convection boundary layer flow along a permeable vertical cylinder with prescribed surface heat flux. The free stream velocity and the surface heat flux were assumed to vary linearly with the distance from the leading edge. The flow and heat transfer characteristics for different values of the governing parameters were analyzed and discussed. Dual solutions for the previously studied mixed convection boundary layer flow over an impermeable surface of the cylinder were shown to exist also in their problem for aiding and opposing flow situations. Very recently, **Rohni et al. [25]** studied numerically by using an implicit finite-difference scheme the laminar steady mixed convection boundary layer flow over a horizontal circular cylinder with constant wall heat flux, immersed in a viscous and incompressible fluid of temperature-dependent viscosity. The effects of temperature-dependent viscosity parameter on the flow and heat transfer characteristics were examined for various values of Prandtl number (Pr) and the mixed convection parameter (λ). It was found that for both assisting and opposing flows, as the viscosity parameter increased, the local skin friction coefficient increased while the wall temperature decreased for air , but for water, the local skin friction coefficient decreased then slightly increased while the wall temperature decreased.

2.3 A cylinder embedded inside a channel or annulus

El-Shaarawi and **Sarhan [26]** investigated numerically the combined forced-free laminar convection in the entry region of a vertical annulus with a rotating inner cylinder under the boundary conditions of one wall being isothermal and the opposite wall adiabatic. The effects of a rotating inner cylinder on the hydrodynamic development length and heat transfer parameters were also studied. **Fusegi et al. [27]** studied the mixed convection flows within a horizontal concentric annulus with a heated rotating inner cylinder. **Ho** and **Tu [28]** considered the laminar mixed convection of the cold water in a vertical annulus with a heated rotating inner cylinder .The results were presented with ranges of $10 \leq Re \leq 200$, and $10^3 \leq Ra \leq 10^6$. They concluded that the combined convection heat and fluid flow structures in the annulus were strongly influenced by the density inversion effects. **Sharma** and **Eswaran [29]** studied the effect of channel-confinement and aiding/ opposing buoyancy on two-dimensional laminar flow and heat transfer across a square cylinder. **Mohammed [30]** studied numerically using finite difference method the laminar air flow mixed convection in the entry region of a vertical annulus with a constant temperature rotating inner cylinder. Numerical results were computed with the ranges of annulus radius ratio ($0.2 \leq N \leq 0.9$), ($-300 \leq Gr/Re \leq 800$) and ($0.2 \leq Re^2/Ta \leq 1000$). He concluded that the thermal boundary layer thickness gradually increased as the flow moved from annulus inlet toward annulus exit. Also , for aiding flow case , the fluid accelerated near the heated boundary and decelerated near the opposite insulated wall and vice versa for opposing flow case. **Teamah [31]** carried out a numerical investigation of double-diffusive laminar mixed convection within a two-dimensional, horizontal annulus. The inner cylinder was considered to rotate in an anti-clockwise direction to introduce the forced convection effect. The solutal and thermal buoyancy forces are sustained by maintaining the inner and outer cylinders at uniform temperatures and concentrations. The streamlines, isotherms and iso-concentrations as well as both local and average Nusselt and Sherwood numbers were studied. The predicted results for both average Nusselt and Sherwood numbers were correlated in terms of Lewis number, thermal Rayleigh number and buoyancy ratio. **Kadhum [32]** performed a theoretical and experimental study on developing laminar air flow mixed convection through an annulus with asymmetric uniformly heated inner and outer cylinders. The experimental results showed that the local Nusselt number values of the aiding flow were higher than that of the opposing flow at the same Reynolds number and heat flux. He concluded that the velocity and temperature profile results indicated that the secondary flow had significant effects on the heat transfer process. **Goharrizi** and **Sadeghi [33]** studied numerically the thermophoretic deposition of aerosol particles in laminar mixed convection flow in a channel with two heated built-in square cylinders. It was found that the temperature gradient near the channel wall, in mixed flow regime, was higher than the temperature gradient in forced convection regime. Also, it was observed that the deposition of particles was increased with the Richardson number and the distance between cylinders was a parameter that influenced the particles deposition. They concluded that the thermophoresis and the inertial impaction were dominant deposition mechanisms of particles on the channel wall. Very recently, **Parvin** and **Nasrin [34]** performed a numerical study to analyze the effects of Reynolds and Prandtl numbers on mixed convective flow and heat transfer inside an octagonal vertical channel in a presence of a heat-generating hollow circular cylinder placed at the centre. All the octagon walls were considered adiabatic. Results were presented in terms of streamlines, isotherms, the average Nusselt number and the maximum fluid temperature for different combinations of Reynolds, Prandtl and Richardson numbers. They concluded that the flow and thermal fields as well as the heat transfer rate and the maximum fluid temperature in the octagonal channel depended significantly on the mentioned parameters.

2.4 Heated or cooled cylinders

Mahmood and **Merkin [35]** investigated the mixed convection boundary-layer flow past an isothermal vertical circular cylinder in both cases when the buoyancy forces aid and oppose the boundary layer development. An approximate solution was derived which gave a good estimate for the heat transfer near the leading edge and had the correct asymptotic form well downstream. In the opposing case, the boundary layer was seen to separate at a finite distance downstream. **Chang** and **Sa [36]** investigated the aiding/opposing buoyancy effect on the vortex shedding in the near wake of a hot/cold circular cylinder at a Reynolds number of 100. They concluded that the cylinder heating impeded the roll up process with subsequent degeneration of the vortex into steady twin vortices at a critical Richardson number of 0.15. **Yoo [37]** numerically simulated the mixed convection of air between two horizontal concentric cylinders with a cooled rotating outer cylinder. **Bassam** and **Abu-Hijleh [38]** solved numerically the problem of laminar mixed convection from an isothermal cylinder. The average Nusselt number was calculated at different values of Reynolds number, Grashof number and incoming free stream angle of attack. Different correlations were presented for a specific range of Reynolds number, buoyancy parameter and angle of attack. **Sharma** and **Eswaran [39]** investigated the aiding and opposing buoyancy effects on the heat and fluid flow across a square cylinder at Reynolds number (Re =100). **Dhiman et al. [40]** analyzed numerically using semi-explicit finite volume method the steady laminar mixed convection flow and heat transfer to Newtonian and power-law fluids from a heated square cylinder. The results were presented for Reynolds number (1-30), power-law index (0.8-1.5) , Prandtl number (0.7-100) and Richardson number (0-0.5).Detailed streamline and isotherm contours were presented to show the complex flow field, especially in the rear of the cylinder. The effects of Prandtl number and power-law index on the Nusselt number were found to be more pronounced than that of buoyancy parameter ($Ri \leq 0.5$) for a fixed Reynolds number in the steady cross-flow regime ($Re \leq 30$). Also, **Dhiman et al. [41]** studied the behavior of steady mixed convection across a confined square cylinder. **Ahmad et al. [42]** numerically studied using an implicit finite-difference scheme the steady laminar mixed convection boundary layer flow past an isothermal horizontal circular cylinder placed in a viscous and incompressible fluid of temperature-dependent viscosity. The solutions were obtained for various values of the Prandtl number (Pr), the mixed convection parameter (λ) and the viscosity/temperature parameter (θ_r). The obtained results showed that the flow and heat transfer characteristics were significantly influenced by these parameters. **Soares et al. [43]** studied the mixed convection characteristics from a circular cylinder immersed in power law fluids when the imposed flow was oriented normal to the gravity direction. The results illustrated that mixed convection distorted streamline , isotherm patterns and increased the drag coefficient as well as the heat transfer rate from the circular cylinder. They observed the complex dependence of all these parameters on power law index ($n = 0.6, 0.8, 1, 1.6$), Prandtl number ($Pr = 1$ and 100), Reynolds number (1−30) and Richardson number (0, 1, and 3). **Srinivas et al. [44]** studied mixed convection heat transfer through the effect of aiding buoyancy from an isothermally heated horizontal cylinder immersed in incompressible power-law fluids in the steady flow regime. The results were presented when both the imposed flow and the buoyancy induced motion were in the same direction. They concluded that the buoyancy effects were stronger in shear-thinning fluids and/or at low Reynolds numbers than that in shear-thickening and/or at high Reynolds numbers. **Kang** and **Iaccarino [45]** computed the turbulent Prandtl number for mixed convection around a heated cylinder in a channel with heating from below. They concluded that the turbulent Prandtl number near by the cylinder illustrated a large variation in space, which implied that the assumption of a single value in the entire flow domain was invalid for their considered problem. Very recently , **Chandra** and **Chhabra [46]** considered steady mixed convection heat transfer from a heated semi-circular cylinder immersed in power-law fluids with its curved surface facing upstream. The numerical results were presented for ($0 \leq Ri \leq 2$), ($0.2 \leq n \leq 1.8$), ($1 \leq Re \leq 30$) and ($1 \leq Pr \leq 100$). At low Reynolds numbers, such as ($Re = 1$), the local Nusselt number was found to be maximum at corners while for high values of the Reynolds number, it shifted towards the front stagnation point. They concluded that the average Nusselt number increased when the Reynolds, Prandtl and Richardson numbers increased.

2.5 Horizontal, vertical and rotating cylinders

Hatton et al. [47] investigated the combined forced and natural convection with low-speed air flow over horizontal cylinders immersed in Newtonian fluids. **Oosthuizen** and **Madan [48-49]** studied the combined convective heat transfer from a heated circular cylinder placed in a horizontal, parallel and contra flow of air as well as 135 degrees with respect to gravity force. They gave various critical Richardson numbers, and suggested that above these critical Richardson numbers the heat convention would transit from forced convection to mixed convection. **Chen** and **Mucoglu [50]** studied using the local non-similarity method the buoyancy effects on forced convection along a vertical cylinder for a uniform wall temperature. **Sparrow** and **Lee [51]** considered the problem of mixed convection boundary layer flow about a horizontal circular cylinder. They obtained a similarity solution for the aiding flow by expanding velocity and temperature profiles using power-law type expressions of the distance from the lowest point of the cylinder. The local Nusselt number distribution was only obtained in the region upstream of the point of separation. **Narain [52]** studied the mixed convection heat transfer and fluid flow from vertical slender cylinder in a uniform stream with isothermal walls. **Oosthuizen** and **Taralis [53]** investigated numerically the mixed convection heat transfer from vertical cylinders in a horizontal fluid flow. **Gorla [54-55]** studied numerically the combined convection heat transfer by considering both the assisting and opposing flow cases in an axisymmetric stagnation flow on a slender impermeable vertical cylinder. The results were presented with an isothermal and linearly increasing temperature respectively for various values of the Prandtl number. **Merkin [56]** studied the combined convection boundary layer on a horizontal circular cylinder in a stream flowing vertically upwards in both cases of a heated and cooled cylinder. It was found that the cylinder heating delayed separation and if the cylinder was warm enough, suppressed it completely. While , the cylinder cooling led the separation point nearer to the lower stagnation point and for a sufficiently cold cylinder there would not be a boundary layer on the cylinder. **Oosthuizen [57]** performed a numerical study of mixed convection heat transfer from a vertical cylinder in a horizontal flow. **Nguyen et al. [58]** studied the combined free and forced convection of water between horizontal concentric cylinders. **Oosthuizen [59]** investigated numerically the combined forced and free convective heat transfer from a horizontal cylinder in an axial stream. **Badr [60-62]** solved the laminar mixed convection heat transfer from an isothermal cylinder with its axis horizontal and perpendicular to the free stream direction and with free stream parallel and opposite to the buoyancy flow for ($1 \leq Re \leq 40$) and ($0 \leq Ri \leq 5$). Moreover , he also investigated the flow direction effect of air on mixed convection in a horizontal cylinder from aiding flow to opposing flow. **Lee et al. [63]** simulated numerically using the finite element method the laminar combined convection flow and heat transfer characteristics from an isothermal horizontal cylinder by solving the full Navier-Stokes and energy equations. **Krauce** and **Tariuk [64]** performed an interferometer study of the mixed convection from a horizontal heated cylinder placed in a contra air flow. **Lee et al. [65]** investigated numerically using a finite difference scheme the mixed convection flow and heat transfer along vertical cylinders and needles under uniform surface temperature boundary condition. **Bui** and **Cebeci [66]** and **Wang** and **Kleinstrever [67]** considered numerically using a finite-difference method the steady laminar combined free and forced convection in vertical slender cylinders for the case of uniform wall temperature. In their works , the buoyancy force effect on the forced convection flow was also investigated. **Heckel et al. [68]** investigated the mixed convection flow of a viscous fluid along a vertical slender cylinders with variable surface temperature. They assumed that the temperature to be arbitrarily varying with the axial coordinate. **Gorla et al. [69]** considered the mixed (forced and free) convection effects in the boundary layer flow of a micropolar fluid on a continuous moving vertical cylinder. **Guo** and **Zhang [70]** investigated the mixed convection in a vertical rotating cylinder. **Ahmad** and **Qureshi [71]** investigated numerically by using the finite difference method the buoyancy effects on forced convection of air from a horizontal cylinder in a cross flow. The results were presented for a wide range of Grashof and Reynolds numbers. **Marcel** and **Regis [72]** investigated numerically the mixed convection heat transfer from vertically separated horizontal cylinders within confining adiabatic walls. They concluded that when the distance between the parallel plates ($L/D \geq 1.5$), the increase in the cylinder spacing led to increase the overall heat transfer coefficient. **Buchlin [73]** examined the natural and forced convective heat transfer along a vertical slender cylinder and also the case of two cylinders. The obtained results indicated that the convective heat transfer had a strong dependence on the cylinder curvature and its misalignment with the main flow. **Takhar et al. [74]** investigated numerically the mixed convection heat and mass transfer along a vertical isothermal moving cylinder with a free stream. Both uniform surface temperature and surface heat flux boundary conditions were investigated. **Pantokratoras [75]** investigated laminar assisting mixed convection from a vertical isothermal cylinder to water with variable physical properties. The temperature range were considered between 20°C and 0°C.The results were obtained with the numerical solution of the boundary layer equations. He concluded that the variation of viscosity , thermal conductivity and density with temperature had a strong influence on mixed convection characteristics. **Mahfouz** and **Badr [76]** investigated numerically the mixed convection from a vertically oscillating cylinder in a quiescent fluid. Their study revealed that the effect of amplitude and frequency of oscillation on heat transfer was strongly influenced by the Grashof number range. They concluded that, at high Grashof numbers, the effect of oscillation on heat convection was only significant at large values of Keulegan-Carpenter number. **Nazar et al. [77]** studied numerically the laminar mixed convection boundary-layer flow of a micropolar fluid past a horizontal circular cylinder in case of constant wall temperature. The solutions for the flow and heat transfer characteristics were evaluated for different parameters, such as the mixed convection parameter, the vortex viscosity parameter and the Prandtl number ($Pr = 1$ and 6.8), respectively. It was found, that their model can be used in industrial problems with polymeric liquids processing, lubricants and molten plastics. **Kumari** and **Nath [78]** simulated numerically using the implicit finite-difference scheme the localized cooling/heating and injection/suction effects on the mixed convection flow in a thin vertical cylinder. A non-uniform distribution of wall temperature and surface mass transfer were considered at certain cylinder sections. The localized cooling/heating and (or) injection/suction effects on the heat transfer were found to be significant, but the cooling/heating effects on the skin friction were comparatively small. They concluded that the positive buoyancy force which assisted the flow and the curvature parameter increased the skin friction and heat transfer. **Pantokratoras [79]** studied the steady laminar opposing mixed convection along vertical isothermal moving plates and cylinders. The bodies were moving upwards while their temperature was lower than the ambient environment. The results were obtained with the direct numerical solution of the boundary layer equations. He observed that the velocity profiles took some interesting shapes that would not been observed previously. **Teamah et al. [80]** studied numerically the mixed convection flow and heat transfer between two horizontal concentric cylinders when the cooled outer cylinder was rotating. They investigated the flow transitions from no cells to one cell and from one cell to two cells with different Prandtl number, radius ratio and rotational Reynolds number. **Kumar et al. [81]** investigated numerically using finite element method , the mixed convection on a moving vertical cylinder with suction in a moving micropolar fluid medium. The effect of micropolar parameter, suction parameter and velocity coefficient parameter had been discussed on the velocity, micro-rotation and temperature functions , when the cylinder velocity was greater than the free stream velocity. It was found that the temperature distribution was moderately effected by the cylinder motion and the buoyancy parameter. **Amoura et al. [82]** investigated numerically using the finite element method the mixed convection problem of non-Newtonian fluid between two coaxial rotating cylinders. The numerical results of the flow and the heat transfer of Carreau's fluid enclosed between two concentric cylinders were presented. **Anwar et al. [83]** numerically studied the steady mixed convection boundary layer flow of a viscoelastic fluid over a horizontal circular cylinder in a stream flowing vertically upwards for both cases of heated and cooled cylinders. Effects of the mixed convection and elasticity parameters on the skin friction and heat transfer coefficients for a fluid having the Prandtl number equals to one were also discussed. It was found that the cylinder heating delayed separation and suppressed the separation completely if the cylinder was warm enough. Also , for a sufficiently cold cylinder there would not be a boundary layer. **Singh** and **Roy [84]** studied the fluid flow and heat transfer characteristics for mixed convection along a rotating vertical slender cylinder. The effects of rotational, buoyancy and suction/injection parameters had been investigated. It was found that the buoyancy force caused a considerable velocity overshoot for low Prandtl number fluids. Numerical results were presented for the skin friction coefficients and for the Nusselt number. **Revnic et al. [85]** investigated the mixed convection flow near an axisymmetric stagnation point on a vertical cylinder. The equations for the fluid flow and temperature fields reduced to similarity form that involved a Reynolds number (R) , mixed convection parameter (λ) and the Prandtl number (σ). The limits of large and small Reynolds number were also treated and the nature of the solution in the asymptotic limit of large Prandtl number was discussed briefly. **Salleh et al. [86]** considered the steady mixed convection boundary layer flow over a horizontal circular cylinder, generated by Newtonian heating in which the heat transfer from the surface was proportional to the local surface temperature. Numerical solutions were obtained for the skin friction coefficient and the local wall temperature as well as the velocity and temperature profiles with the mixed convection parameter and the Prandtl number. **Nadeem et al. [87]** performed an analysis to obtain the similarity solution of the steady mixed convection boundary layer flow and heat transfer of a second grade fluid through a horizontal cylinder. The resulting non-linear coupled system of the ordinary differential equations subject to the appropriate boundary conditions was solved by homotopy analysis method (HAM). The behavior of skin friction coefficient and Nusselt numbers was studied for different parameters. **Lok et al. [88]** considered the steady mixed convection flow near an axisymmetric stagnation point on a stretching or shrinking vertical cylinder. The fluid flow and temperature fields equations were reduced to similarity form that involved a Reynolds number, mixed convection parameter , cylinder motion parameter and the Prandtl number. The resulting equations were solved numerically in both the aiding and opposing flow cases for representative values of the considered parameters. Very recently, **Wang [89]** studied the flow and natural (or mixed) convection due to a vertical stretching cylinder. Asymptotic analysis for large Reynolds numbers showed the relation between axisymmetric flow and two-dimensional flow. The axial velocity was composed of forced convection due to stretching and natural convection from the heated cylinder. He concluded that the heat transfer increased with both the Reynolds and Prandtl numbers.

2.6 Experimental studies

Oosthuizen and **Barnes [90]** carried out an experimental study of mean combined convective heat transfer rates from oblong cylinders to air. **Fand** and **Keswani [91]** experimentally investigated the heat transfer rate in the combined natural and forced convection heat transfer from a horizontal cylinders to water in the cross-flow configuration. According to the Richardson number value (Ri), they identified four heat transfer regimes. They concluded that when ($Ri \leq 1$), buoyancy effect was insignificant in the flow while, for ($Ri \geq 1$), it became more important. **Oosthuizen** and **Bishop [92]** investigated experimentally the mixed convective heat transfer from square cylinders. **Oosthuizen** and **Henderson [93]** performed an experimental study of mixed convection heat transfer from tandem cylinders in a horizontal air flow. **Hu** and **Koochesfahani [94]** investigated experimentally the wake behavior behind a heated circular cylinder in forced and mixed convection regimes. The experiment was conducted in a water channel with the temperature and Reynolds number of the approaching flow were considered constant. With increasing Richardson number, significant modifications of the wake instability were revealed from both qualitative flow visualization images and quantitative simultaneous velocity and temperature fields. The buoyancy effect on the wake instability of the heated cylinder was discussed in terms of vortex shedding pattern and frequency, turbulent heat flux distribution, the wake closure length and averaged Nusselt number of the heated cylinder. **Champigny et al. [95]** studied experimentally the mixed convection flows and its associated heat transfers, around a large vertical cylinder. The experiment included a finite heated cylinder cooled by a transverse air flow, inside an insulated tunnel where the Reynolds number was 43000. The air flow profiles and temperatures and the cylinder wall temperatures issued from numerical calculations were analyzed and averaged results were compared with the experimental ones. **Mohammed** and **Salman [96]** performed an experiments to study the local and average heat transfer by mixed convection for hydrodynamically fully developed, thermally developing and thermally fully developed laminar air flow in an inclined circular cylinder. The investigation covered Reynolds number range from 400 to 1600, heat flux was varied from 70 W/m^2 to 400 W/m^2 and cylinder angles of inclination including 30^o, 45^o and 60^o.The results presented the surface temperature distribution along the cylinder length, the local and average Nusselt number distribution with the dimensionless axial distance. For all entrance sections, the results showed an increase in the Nusselt number values as the heat flux increased and as the angle of cylinder inclination moved from ($\theta=60^o$) inclined cylinder to ($\theta=0^o$) horizontal cylinder. Also, the average Nusselt numbers have been correlated with the (Rayleigh numbers/Reynolds numbers) in empirical correlations. **Mohammed** and **Salman [97]** experimentally studied combined convection heat transfer in a vertical circular cylinder for assisting, thermally developing and thermally fully developed laminar air flows under constant wall heat flux boundary conditions. They examined the cylinder inclination angle effect on the mixed convection heat transfer process. The experimental setup consisted of aluminum cylinder with (30 mm) inside diameter and (900 mm) heated length (L/D=30).They concluded that for the same heat flux and low Reynolds number, the local Nusselt number increased as the cylinder angle of inclination moved toward horizontal cylinder. It was found also that the lower value of local Nusselt number occurred at ($\theta=90°$) vertical cylinder and the higher value occurred at ($\theta=0°$) horizontal cylinder when the free convection was the dominating factor on the heat transfer process. **Singh et al. [98]** investigated experimentally the buoyancy effect on the wakes behind heated circular and square cylinders at low Reynolds numbers. The electrically heated cylinder was mounted in a vertical airflow facility such that buoyancy aided the inertia of main flow. The Reynolds and Richardson numbers were varied to examine flow behavior over a range of experimental conditions from forced to mixed convection regime. Laser schlieren-interferometry was used for visualization and the flow structures analysis. They concluded that the convection velocity of vortices increased in stream wise direction to an asymptotic value and its variation was a function of Richardson number. **Mohammed** and **Salman [99]** performed an experimental investigation of combined convection heat transfer for thermally developing flow in a horizontal circular cylinder. They presented various values of surface temperature related to the horizontal circular cylinder. **Ko et al. [100]** performed a series of the turbulent mixed convection heat transfer experiments in a vertical cylinder. The tests in buoyancy-aided and opposed flow configurations, were performed for Reynolds numbers from 4000 to 10,000 with a constant Grashof number of 6.2×10^9 and Prandtl number of about 2000.They indicated that the experimental method simulated the mixed convection phenomena successfully and proved itself to be a useful tool for the draft estimation of the heat transfer rate in the highly buoyant systems.

3. Conclusions

The present work gives a comprehensive overview and understanding of about one-hundred published papers related with combined free and forced convection in cylinders. The reviewed papers have been collected , explained carefully and classified in different sections according to their specification. We think that more analytical , numerical and experimental researches are required to study the flow and thermal characteristics of combined free and forced convection in cylinders and to produce another important papers for this subject.

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