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HEAT TRANSFER AUGMENTATION WITH ALUMINIUM OXIDE NANOFLUID IN A PLAIN TUBE AND WITH INSERTS

(PENAMBAHAN KADAR PEMINDAHAN HABA MENGGUNAKAN BENDALIR-NANO ALUMINIUM OKSIDA DALAM TIUB BIASA DAN DENGAN SISIPAN)

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ABSTRACT

HEAT TRANSFER AUGMENTATION WITH ALUMINIUM OXIDE NANOFLUID IN A PLAIN TUBE AND WITH INSERTS

(Keywords: nanofluids, heat transfer augmentation, twisted tapes)

Theoretical investigation of nanofluid heat transfer under turbulent flow in a tube has been undertaken for a wide range of Reynolds number. A model is proposed for the development of eddy diffusivity equation applicable to nanofluids. The numerical results obtained from the model are compared with the experimental data of different investigators. Equations are developed for the estimation of thermo-physical properties of nanofluids for input parameters viz., temperature, nano particle size and concentration. The viscosity of nanofluid is observed to increase with particle size and decrease with temperature, whereas the thermal conductivity decreases with particle size and increases with temperature. It is found that the values of heat transfer coefficients evaluated with the equations are in good agreement with the experimental results. The theoretical determination of Nusselt number for flow in a tube with twisted tape insert has been undertaken for the first time. The results obtained for flow in a tube with twisted tape are in good agreement with the experimental data. Relevant regression equations are developed for the estimation of Nusselt number. The Colburn type equation is developed for the prediction of Nusselt number where the friction factors are to be estimated with the Blasius equation;

$$St\,\mathrm{Pr}_w^{2/3} = \frac{f}{8}\left(1+\phi\,\mathrm{Pr}_w\right)^{0.1185}$$

$$Nu = 0.0304\,\mathrm{Re}^{0.7853}\,\mathrm{Pr}^{0.4}\,[0.001+\phi]^{0.01398}$$

$$St\,\mathrm{Pr}^{2/3} = 1.0344\left(\frac{f_{tt}}{8}\right)\left(1.0+\phi\right)^{0.1479}\left(1.0+\frac{D}{H}\right)^{0.2445} \quad \text{where}$$

$$f_{tt} = 0.4818\,\mathrm{Re}^{-0.2731}\left(0.001+\phi\right)^{0.00061}\left(0.001+D/H\right)^{0.0296}$$

The Nusselt number estimated with these equations predict are validated for water base nanofluids for $\phi \le 3.7\,\%$, $3000 \le \mathrm{Re} \le 70000$ and $1.4 \le \mathrm{Pr} \le 10.0$. An experimental setup for the estimation of forced convection heat transfer coefficients is designed, commissioned and in working condition. All the three objectives envisaged in the project are achieved.

ABSTRAK

PENAMBAHAN KADAR PEMINDAHAN HABA MENGGUNAKAN BENDALIR-NANO ALUMINIUM OKSIDA DALAM TIUB BIASA DAN DENGAN SISIPAN

(Kata kunci: nano-bendalir, penambahan pemindahan haba, pita bengkok)

Kajian teori berkaitan pemindahan haba nano-bendalir untuk aliran gelora dalam tiub biasa telah dijalankan untuk nombor Reynolds dalam julat yang besar. Sebuah model telah dicadangkan untuk pembangunan persamaan peresapan eddy yang amat berguna kepada bendalir-nano. Keputusan berangka yang diperolehi daripada model dibandingkan dengan data eksperimen yang dihasilkan oleh penyelidik yang berlainan. Persamaan-persamaan untuk menganggar sifat-sifat termo-fizikal bendalir-nano telah dihasilkan dengan menggunakan parameter-parameter masukan berikut iaitu suhu, saiz zarah nano dan kepekatan. Kelikatan bendalir-nano didapati meningkat dengan pertambahan saiz zarah, dan menurun dengan pertambahan suhu, sedangkan konduktiviti haba menurun dengan pertambahan saiz zarah dan meningkat dengan suhu. Nilai-nilai pekali pemindahan haba yang dikira menggunakan persamaan-persaman tadi didapati mempunyai keputusan yang sama dengan data daripada eksperimen. Penentuan nilai teori nombor Nusselt untuk aliran dalam tiub biasa bersama sisipan pita bengkok telah dilakukan untuk pertama kalinya. Keputusan yang diperolehi untuk aliran dalam tiub biasa biasa bersama sisipan pita bengkok memberikan nilai yang menyamai dengan data eksperimen. Persamaan-persamaan regresi yang berkaitan telah dibangunkan untuk menganggar nombor Nusselt. Persamaan jenis Colburn dihasilkan untuk mengira nombor Nusselt; di mana pekali-pekali geseran dianggarkan menggunakan persamaan Blasius

$$St\,\mathrm{Pr}_w^{2/3} = \frac{f}{8}\left(1+\phi\,\mathrm{Pr}_w\right)^{0.1185}$$

$$Nu = 0.0304\,\mathrm{Re}^{0.7853}\,\mathrm{Pr}^{0.4}\,[0.001+\phi]^{0.01398}$$

$$St\,\mathrm{Pr}^{2/3} = 1.0344\left(\frac{f_{tt}}{8}\right)\left(1.0+\phi\right)^{0.1479}\left(1.0+\frac{D}{H}\right)^{0.2445} \quad \text{di mana}$$

$$f_{tt} = 0.4818\,\mathrm{Re}^{-0.2731}\left(0.001+\phi\right)^{0.00061}\left(0.001+D/H\right)^{0.0296}$$

Nombor Nusselt dikira menggunakan persamaan-persamaan anggaran ini disahkan untuk bendalir-nano berasaskan air bagi keadaan $\phi \le 3.7\,\%$, $3000 \le \mathrm{Re} \le 70000$ dan $1.4 \le \mathrm{Pr} \le 10.0$. Sebuah eksperimen untuk menganggar pekali pemindahan haba olakan paksa telah direkabentuk, dipasang dan berfungsi dengan baik. Ketiga-tiga objektif yang telah disasarkan dalam projek ini semuanya telah berjaya dicapai.

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B	eddy diffusivity coefficient
b	bulk
C	specific heat, J/kg K
C_f	Fanning friction factor
D	inner diameter of the tube, m
d	diameter of nanoparticle, (m)
δ	thickness of strip, m
ε_H	Thermal eddy diffusivity, (m^2/s)
ε_m	Momentum eddy diffusivity, (m^2/s)
f	friction coefficient
ϕ	volume fraction of nanoparticles (%)
g	gravitational force acceleration, m^2/s
H	pitch for 180° rotation, m
h	mean heat transfer coefficient, $W/(m^2K)$
H/D	twist ratio, dimensionless
j	Colburn factor
K	thermal conductivity, J/ (K m)
μ	absolute viscosity, kg/(m.s)
nf	nanofluid
Pr	Prandtl number,
p	nanoparticle
ΔP	pressure difference
Re	Reynolds number
R^+	dimensionless radius
ρ	density, (kg/m^3)
St	Stanton number
T	temperature, $^\circ C$
τ_{wall}	wall shear stress
T^+	dimensionless temperature

u	velocity, (m/s)
u^*	shear velocity
u^+	dimensionless velocity, (u/u^*)
V	average fluid velocity, m/s
ν	Kinematic viscosity, (m^2/s)
w	water
y	distance measured normal to the wall, (m)
y^+	dimensionless distance measured normal to the wall,
ζ	Prandtl index

LIST OF ABBREVIATIONS

AD	average deviation
CFD	Computational Fluid Dynamic
CNT	Carbon Nano Tubes
DW	Distilled Water
EG	Ethylene glycol
HP	Horse Power
MWCNT	Multi Walled Carbon Nano Tubes
SD	standard deviation
SDBS	Sodium Dodecyl Benzene Sulfonate

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Heat transfer fluids such as water, mineral oils and ethylene glycol play an important role in many industrial sectors including power generation, chemical production, air-conditioning, transportation and microelectronics. The performance of these conventional heat transfer fluids is often limited by their low thermal conductivities. Driven by industrial needs of process intensification and device miniaturization, development of high performance heat transfer fluids has been a subject of numerous investigations in the past.

Various methods for heat transfer enhancements have been developed over the years either to accommodate high heat fluxes in the limited area available or to reduce the size and consequently the cost in order to compete in the global market. This augmentation of heat transfer can be achieved through active and passive methods. In the classification under active type, heat transfer enhancement is associated using external energy on the fluid through forced flow/vibration/injection/suction/jet impingement and the use of electrostatic fields. Under passive augmentation, enhancement of heat transfer can be due to artificially roughed surface, extended surface, swirl flow with twisted tape inserts, convoluted or twisted tube, use of additives in liquids and gases.

Passive method of heat transfer enhancement is advantageous to achieve high heat transfer rates with minimum pressure drop. Twisted tapes are commonly used for enhancing convective heat transfer by introducing swirl into the bulk flow. The tape disrupts the boundary layer formation and induces turbulence even at low flow rates thereby enhancing the heat transfer coefficients.

Another passive method is by adding additives to liquids. Solid particles have thermal conductivities several times higher than those of conventional fluids. Ultra fine solid particles can be used to suspend them uniformly to enhance the thermal conductivity of the fluid. Metallic, non-metallic and polymeric particles can be added to liquids to form slurries. However the usual slurries with suspended particles of the order of millimeters or even micrometers can cause severe problems such as clogging, erosion, etc. associated with higher pressure drop. Furthermore, they suffer from instability and rheological problems.

The use of nanometer size particles for use as heat transfer fluid is initiated by a research group at the Argonne National Laboratory. Choi (1995) coined the word 'nano fluids' who observed very high values of thermal conductivity compared to suspended particles of millimeter or micrometer dimension. The nanofluids showed better stability and rheological properties, dramatically higher thermal conductivities with no significant penalty on pressure drop. Most of the experiments in literature are focused on the theoretical prediction and measurement of thermal conductivity of the nanofluids.

1.2 PROBLEM STATEMENT

Experiments are conducted to determine the thermal conductivity, viscosity and heat transfer coefficients in the turbulent Reynolds numbers range at different temperatures, with nano materials and particle sizes in the low volume concentration. Suitable equations for the determination of thermo physical properties valid for water based nanofluid in volume concentration of less than 4% are not available in literature. Further, theoretical evaluation of nanofluid heat transfer coefficients for flow in a plain tube and with twisted tape insert is not reported till now.

1.3 OBJECTIVES OF THE RESEARCH

The objectives of this project are as follows:

i. Estimation of certain thermo-physical properties of Al_2O_3 nanofluid in the volume concentration range of 0.0% to 4.0 %.

ii. Fabrication of an experiment setup for the estimation of heat transfer coefficient and friction factor of Al_2O_3 nanofluid at different volume concentrations in the Reynolds number range of 3,000 to 22,000 in a plain tube subject to constant heat flux boundary condition.

iii. Develop equations for the estimation of Nusselt number and friction factor for comparison with other equations in literature for the case of a plain tube and with tape inserts

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

A number of studies have been performed to investigate the transport properties of nanofluids, Eastman et al.(1997), Wang et al.(1999), Lee et al.(1999) and Xuan and Li (2000). These studies are concentrated on the evaluation of effective thermal conductivity under macroscopically stationary conditions. Limited studies on other aspects related to nanofluids such as phase change behavior has been due to Das et al.(2003), Tsai et al.(2003), You et al.(2003) and Vassallo et al.(2004).

Dittus – Boelter (1930), Gnielinski (1976), Tam and Ghajar (2006) and Churchill and Usagi (1972) developed correlations for the estimation of heat transfer coefficient of single-phase fluid flow in a circular tube under fully developed and transition flow conditions for constant heat flux boundary condition. Pak and Cho (1998) estimated convective heat transfer coefficients in the turbulent Reynolds number range with Al_2O_3 and TiO_2 nanofluids dispersed in water and observed that the Nusselt number of the nanofluids increased with increasing volume fraction of the suspended nanoparticles and the Reynolds number. Xuan and Li (2003) estimated convective heat

of pure water. Wen and Ding (2004), Yang et al. (2005), Heris et al. (2007) investigated the convective heat transfer of Al_2O_3 nanofluid in a circular tube under laminar flow conditions subjected to constant heat flux. They observed the heat transfer rates to increase with increasing concentration of submicron particles to the base fluid.

Heris et al. (2006) conducted experiments in the laminar range with Al_2O_3 and CuO nanofluids and observed Al_2O_3 nanofluid to have higher heat transfer rates compared to CuO nanofluid.

Single phase heat transfer enhancement with twisted tape inserts under laminar and turbulent flow conditions have been dealt by Smithberg and Landis (1964), Manglik and Bergles (1993) and Sarma et al. (2002). Experiments with nanofluids for heat transfer enhancements in a plain tube and with twisted tape inserts is reported by Sundar and Sharma (2010) for low volume concentration in the turbulent range.

2.2 HEAT TRANSFER COEFFICIENT IN A PLAIN TUBE

2.2.1 Forced Convection in a Plain Tube - Numerical Studies

Maiga et al. (2005) conducted numerical investigations to determine heat transfer coefficients with Al_2O_3/water and Al_2O_3/EG nanofluids under laminar flow in a tube assuming negligible slip between the particles and the continuous phase. Correlations for the estimation of Nusselt number for the case of constant heat flux and wall temperature are presented. Numerical analysis of laminar flow heat transfer in a tube with Al_2O_3 /EG and Al_2O_3/water nanofluids has been reported by Palm et al. (2004) and Roy et al. (2006). They observed the wall shear to increase with particle volume concentration and Reynolds number. Buongiorno (2006) concluded from his theoretical analysis that Brownian diffusion and thermophoresis are important mechanisms and that energy transfer by nanoparticle dispersion is negligible. The author opines that decrease in nanofluid viscosity in the boundary layer due to large temperature gradient and thermophoresis result in enhanced heat transfer. Experimental studies by Behzadmehr et al. (2007) with Cu nanoparticles in water at 1.0% vol. concentration under turbulent forced convection is found to be in good agreement with results from Computational Fluid Dynamic (CFD) mixture model. Determination of heat transfer coefficients using CFD analysis for CuO, Al_2O_3 and SiO_2 nanoparticles dispersed in ethylene glycol and water mixture in 60:40 mass ratio, at 6% volume concentration has been undertaken by Namburu et al. (2008). They observed that the values of friction factor obtained in the turbulent Reynolds number range can be represented with the Blasius equation and the heat transfer coefficients with the equation of Gnielinski (1976). Comparison of experimental values of heat transfer coefficients with TiO_2/water nanofluid and CFD results by Yurong He et al. (2009) indicate close agreement in the laminar developing region. They concluded from their analysis that the variation of thermal conductivity has greater influence on heat transfer coefficient than viscosity. Izadi et al. (2009) have undertaken numerical investigations of the laminar developing flow in an annulus with the properties of Al_2O_3 nanofluid in base liquid water. They observed the temperature profiles to be affected significantly but not the dimensionless axial velocity with changes in volume concentration. Bianco et al. (2009) conducted numerical investigation of developing flow in tubes with Al_2O_3/water nanofluid at 1.0 and 4.0% vol. concentration. Both single and discrete (two) phase model is employed in the analysis for a particle size of 100 nm. The results indicate a deviation of 11% between the values of heat transfer coefficient obtained from these two models. They observed higher heat transfer coefficients and lower shear stresses when thermal conductivity and viscosity are considered temperature dependent.

2.2.2 Forced Convection in a Plain Tube – Experimental determination

Preliminary experiments for the determination of thermo-physical properties and forced convection heat transfer coefficients with Al_2O_3 and TiO_2 submicron particles dispersed in water is due to Pak and Cho (1998). They conducted hydrodynamic and heat transfer experiments with nanofluids and obtained higher heat transfer coefficients which increased with concentration and Reynolds number. The nanofluid viscosity and thermal conductivity is observed to vary with volume concentration and temperature. However, the regression equation for Nusselt number presented is independent of volume concentration. Xuan and Roetzel (2000) proposed thermal dispersion as a major mechanism for heat transfer enhancement of a flowing nanofluid. Xuan and Li (2003) conducted experiments with Cu/water nanofluid at different particle volume concentrations of up to 2.0%. They opined that the dispersion will flatten the temperature distribution and make the temperature gradient between the fluid and the wall steeper. The regression equation for Nusselt number developed by them includes volume concentration and particle Peclet number. No significant enhancement in nanofluid friction factor is observed when compared to values of water in the experimental range. Also, the experiments by Eastman et al. (2001) with less than 1% CuO nanofluid under turbulent flow condition showed enhancements of heat transfer coefficient by more than 15% in comparison to similar conditions obtained with water.

Forced convection experiments conducted by Nguyen et al. (2007) in the Reynolds number range of $3000 < \mathrm{Re} < 7000$ and volume concentration $\phi < 6.8\,\%$ predicted higher heat transfer coefficients with 36nm size Al_2O_3/water nanoparticles compared to values evaluated with 47nm size particles. Heris et al. (2006) conducted experiments for the determination of convection heat transfer coefficients in the laminar flow range of $650 < \mathrm{Re} < 2050$ with Al_2O_3 and CuO nanofluids in water at volume concentration $\phi < 3.0\,\%$. They observed the values of heat transfer coefficients with Al_2O_3 nanofluid greater than CuO nanofluid at large volume fractions. However, they have not presented equation for the estimation of Nusselt number.

Experiments conducted by Yulong Ding et al. (2006) with multi walled carbon nanotubes with 0.5% weight concentration showed enhancement in convective heat transfer coefficients of over 350% at Reynolds number of 800. The authors attributed the abnormal enhancement to possible particle rearrangement, reduction of thermal boundary layer, high aspect ratio of nanotubes besides enhanced thermal conductivity. In another paper, Yulong Ding et al. (2007) observed convection heat transfer with Carbon Nanotube/water, Titanate Nanotube/water and TiO_2/water nanofluids exceed enhancements in thermal conduction. They opined that clustering of nanoparticles as a dominant mechanism responsible for enhanced heat transfer.

Yurong He et al. (2007) observed an increase in convective heat transfer coefficient of TiO_2 nanofluid with volume concentration $\phi \leq 1.0\,\%$ in both laminar and turbulent flow regimes. They observed the influence of nanoparticle concentration on heat transfer coefficient to be significant in the turbulent than in laminar region. Gwan Hyun Ko et al. (2007) observed that the nanofluid friction factor obtained with Multi Walled Carbon Nano Tubes (MWCNT) in water of 1400 ppm concentration and stabilized with surfactant predict higher values when compared with MWCNT nanofluid prepared by acid treatment. The nanofluids showed larger pressure drop when compared to values with distilled water in the laminar range. However, in the turbulent range the values of pressure drop obtained with the nanofluids are close to that of water.

Williams et al. (2008) conducted experiments to estimate turbulent convective heat transfer coefficients with Al_2O_3 and ZrO_2 nanofluids dispersed in water for $9000 \le \mathrm{Re} \le 63000$, $21 \le T_b \le 76\,^{\circ}\mathrm{C}$ and maximum volume concentration of 3.6 and 0.9% respectively. They concluded that the existing correlations of single phase flow can be used to predict the convective heat transfer coefficient and pressure drop of the nanofluids. Kyo Sik Hwang et al. (2009) conducted experiments with Al_2O_3 nanofluid and observed 8 % enhancement in heat transfer coefficients at a particle volume concentration of 0.3 % in the fully developed laminar range. The flattening of the velocity profiles observed by them is attributed to large gradients observed with properties responsible for enhanced heat transfer coefficients.

Doohyun Kim et al. (2009) conducted experiments with water based alumina and amorphous carbonic nanoparticles for flow in a tube under laminar and turbulent conditions. A 20% increment in convective heat transfer coefficient at 3.0% volume concentration is reported with alumina nanofluid. They concluded from their experiments that carbonic nanofluid did not show promise as an enhanced heat transfer fluid in the turbulent range. Yu et al. (2009) conducted experiments with 170 nm SiC nanoparticles in water at volume concentration of 3.7% in the range $3300 < \mathrm{Re} < 13000$, $4.6 < \mathrm{Pr} < 7.1$ and observed 50-60 percent enhancements in heat transfer. They concluded from their experimental analysis that SiC/water is a better heat transfer liquid and requires lower pumping power compared to Al_2O_3/water nanofluid.

TiO_2 nanofluid with particle size of 21nm is used to conduct heat transfer experiments in a double pipe heat exchanger in the range of $0.2 < \phi < 2.0\,\%$, $3000 < \mathrm{Re} < 18000$ by Duangthongsuk and Wongwises (2010) with water as the heating medium. The heat transfer coefficients of the nanofluid are found to increase with Reynolds number and volume concentration upto 1.0%. The heat transfer coefficient decreased with further increase in volume concentration but is observed to be greater when compared to values with water. However, Pak and Cho (1998) observed the heat transfer coefficients with 3.0% TiO_2 nanofluid with 27nm particle size to be 12% lower than that of water. Fotukian and Esfahany (2010) conducted experiments in the range of $6000 < Re < 31000$ for flow in a tube with CuO nanofluid of maximum volume concentration of 0.024%. They observed 25% enhancement in heat transfer coefficients and 20% higher pressure drop compared to values obtained with base liquid water. However most of the investigators have concluded that the pressure drop with nanofluids is close to the values of water in the turbulent range.

Estimation of heat transfer coefficients have been made mostly through experimental investigations with Al_2O_3, Cu, CuO, SiC, TiO_2, etc nanoparticles dispersed in water. The investigators used different particle sizes, concentration and temperature range in their experiments having limitation for comparison of either properties or heat transfer coefficients with others. Also the theoretical analysis for the estimation of heat transfer coefficient reported in literature is scarce.

Hence using the available experimental data, equations are developed to determine the influence of particle size, concentration and temperature on thermo-physical properties and utilize them for the theoretical estimation of heat transfer coefficients with the eddy diffusivity equations developed by Sarma et al. (2010).

2.3 HEAT TRANSFER COEFFICIENT WITH TWISTED TAPES

2.3.1 Forced Convection with Twisted Tape – Experimental determination

Passive heat transfer augmentation using twisted tapes, longitudinal inserts, wire coil insert, etc for a wide range of Reynolds and Prandtl numbers have been reported by Bergles (1988). The twisted tape causes the flow to swirl, providing longer path length and residence time and thereby enhancing heat transfer. However, the pressure drop with insert is higher due to the resistance offered by the additional tape surface area when compared to flow in plain tubes.

Experimental studies are conducted by Smithberg and Landis (1964) with air as the working medium. They observed that increased frictional loss is due to the vortex flow caused by the twisted tapes which continuously mixes the core flow with the vortex flow and developed a semi-empirical model for the estimation of friction factor. Thorsen and Landis (1968) extended the analysis and developed correlation for the estimation of Nusselt number using experimental data of water. Lopina and Bergles (1969) developed a superposition model for the estimation of Nusselt number to account for the increased speed of flow due to tape insert and the centrifugal buoyancy effects in the tube. They observed an increase of 20% in the Nusselt number for tight fit tapes compared to reduced width tapes. Manglik and Bergles (1993) conducted experimental investigations on isothermal tubes with twisted-tape inserts using water and ethylene glycol in the turbulent Reynolds number range and developed correlation based on the asymptotic method. Saha and Dutta (2001) conducted themo-hydraulic studies in a circular tube fitted with twisted tapes for a wide range of Prandtl numbers (205<Pr<518) in the laminar Reynolds number range under constant wall heat flux boundary condition. They used twisted-tape inserts having short-length, regularly spaced with multiple twists in the tape module which is connected by thin circular rods and smoothly varying (gradually decreasing) pitch twisted-tapes and observed that reducing tape widths resulted in poor heat transfer where as the difference between the heated friction factor and isothermal friction factor is less for a periodic swirl flow compared to that of a plain tube.

Bandyopadhyay et al.(1991) carried out experiments with viscous oil to determine the influence of free convection on heat transfer in the laminar Reynolds number range. They classified flow regime into three types, the first with secondary flow due to swirl, the second as transition flow and the third as secondary flow due to free convection in their respective zones and compared the results with the correlation of Hong and Bergles (1976) and other free convection correlations. Agarwal and Raja Rao (1996) conducted experiments for flow with tape inserts in circular tubes under uniform wall temperature using Servotherm oil and developed correlations for the evaluation of heat transfer coefficients and friction factor. Naphon (2006) has undertaken experimental studies in plain tubes and with twisted tape inserts and developed correlations for the estimation of heat transfer and pressure drop in turbulent Reynolds number range $7000 < \mathrm{Re} < 23000$ and for twist ratio (H / D) between 3.1 and 5.5. Experiments to determine heat transfer coefficient under laminar flow of water in a tube with different twisted tape inserts in vertical and horizontal orientations were carried out by Klaczak (2001). At low flow rates, it is observed that natural convection effects dominated and heat transfer rates are higher with twisted tape insert in vertical compared to horizontal orientation. Herwig and Kock (2006) developed a tool from thermodynamic point of view for evaluating heat transfer performance under turbulent flow in a pipe with twisted tape inserts. Turbulence modelling of the flow phenomenon indicated a reduction in overall entropy production for a certain range of twist ratio when compared to flow in a plain tube. Mazen Abu-Khader (2006) investigated the behavior of heat transfer in a shell and tube heat exchanger for different twist ratios for a wide range of flow Reynolds number. It is observed that pressure drop increased sharply with decrease in tube diameter. However, the Nusselt number increased significantly with twist ratio in the laminar Reynolds number range. Akhavan-Behabadi et al. (2008) conducted experiments at different mass flow rates and developed correlations and determined heat transfer coefficients during condensation of R-134a refrigerant in a plain tube and with twisted tape inserts. Ayub and Al-Fahed (1993) observed experimentally the effect of gap between the tube and tape insert on pressure drop for turbulent flow of water. The pressure drop increased with decrease of gap width and increase of tape width.

Experiments with nanofluid are conducted by Sharma et al. (2009) and Sundar and Sharma (2010) for the determination of heat transfer coefficients in a tube and with tape inserts applicable in the transition and turbulent range of Reynolds number, respectively. The values of Nusselt number is compared for water with the equation of Gnielinski (1976) and for nanofluid with the equation of Pak and Cho (1998) under turbulent flow conditions for flow in a plain tube. A satisfactory agreement of the experimental data with these equations has been observed. Hence, based on the reliability of the values obtained, experiments are carried out with water and nanofluid with tape inserts in a tube at different flow conditions.

2.3.2 Forced Convection with Twisted Tapes - Theoretical Analysis

Theoretical analysis for the estimation of heat transfer coefficient of pure fluids with twisted tape insert has been documented. The theoretical modelling considers the effect of turbulence due to spiralling flow and heat conduction in the tape. Date (1974)