NUMERICAL STUDY ON THE EFFECT OF INCLINATION ANGLE ON HEAT TRANSFER PERFORMANCE IN BACK-WARD FACING STEP UTILIZING NANOFLUID

Saleh Etaig*, Etaig.Mahmoud@Northumbria.ac.uk

Reaz Hasan, Reaz.Hasan@Northumria.ac.uk

Noel Perera, Noel.Perera@Northumbria.ac.uk

ABSTRACT

This paper reports a numerical investigation the effect of inclination angle of the vertical face of a backward-facing step on the heat transfer performance utilizing Nanofluid for laminar flow. Al2O3 is the nanoparticle used in this investigation, and water is the base fluid. The finite volume technique is used to solve the momentum and energy equation in 2D backward facing step geometry with an expansion ration of 1.5. The effect of Re on Nu is investigated for the Reynolds numbers 40, 100 and 150 and for different volume fractions of the nanoparticles of 2%, 4% and 6% for all simulations. Nusselt number distribution at the bottom wall is computed. Pressure losses also reported for different Reynolds numbers and entropy is studied for a range of Reynolds numbers and for different volume fractions of Nanofluid. The results are validated with available literature. Four angles of inclination of the vertical step is investigated 90^o,97.5^o,105^o and 115^o. The effect of the inclination angle on the heat transfer showed that the heat transfer was enhanced with a decrease in the inclination angle.

INTRODUCTION

Separations in flows due to the adverse pressure gradient can be encountered in many industrial applications such as electronic cooling, passage of turbine blades, combustors, and many heat exchangers. Backward facing step is one of the basic configurations where flow separation takes place. The separation and reattachment of the flow play a vital role in determining the flow structure and affect the heat transfer performance. A significant amount of high fluid energy occurs in the reattachment region of these devices. There are several ways to enhance heat transfer, one of which is to employ nanofluids. Nanofluids are formed by dispersing nanoparticle in a base fluid; the base fluid could be water, ethylene glycol or oil. The application of nanofluids in many industrial application are investigated by many researchers since the first research by (Choi and Eastman, 1995). There were many studies focused on the flow separation and reattachment in the past decades, and the BFS geometry received much attention. (Armaly et al., 1983) conducted an experimental work on backward facing step to investigate the reattachment length. (Biswas et al., 2004) investigated Laminar backward-facing step flow for a wide range of Reynolds numbers and expansion ratios in two and three-dimensional simulations. The finding was that this primary recirculation length increases non linearly with increasing expansion ratio. (Abu-Nada, 2006) presented a numerical study of entropy generation over a 2D backward facing step with various expansion ratios and the results showed that total entropy generation increases with the increase in Reynolds number.. (Mohammed et al., 2011) studied the effect of Nanofluids on heat transfer performance in Backward facing step and found that there is a primary recirculation region for all nanofluids behind the step and the skin friction coefficient is sensitive to the recirculation flows. (Pour and Nassab, 2012) has numerically studied the convective flow of nanofluids with different volume fractions over a BFS under bleeding condition. They found that the recirculation zones and the reattachment length increase as bleed coefficient increases. (Togun et al., 2014) investigated numerically the effect of volume fraction on the heat transfer rate using nanofluid, the results showed that the recirculation flow as created by the backward-facing step enhanced heat transfer. (Erturk, 2008) presented a comprehensive numerical work of the 2-D steady incompressible backward-facing step flow, the results showed that, for the backward-facing step flow an inlet channel that is at least five step heights long is required for accuracy, he also found that the size of the recirculating regions grows almost linearly as the Reynolds number increases. (Lan et al., 2009) reported the effect of aspect ratio and the Re number on the flow and the heat transfer performance and showed that the effect of Re on the flow reattachment is minimal in the range of the parameters. (Mohammed et al., 2015) carried out Numerical simulation of laminar and turbulent mixed convection heat transfers of nanofluid flow over backward facing step placed in a horizontal duct having baffle. They reported that Nusselt number and velocity distribution increased gradually by increasing the Reynolds number of laminar and turbulent flows. (Kherbeet et al., 2014a) and (Kherbeet et al., 2014b) studied numerically and experimentally the heat transfer characteristic of nanofluid laminar flow over the microscale backward facing step. They also carried out a simulation of three dimensional laminar mixed convection to study the effect of step height on the flow and heat transfer characteristics. They found that the Nusselt number increase with increases volume fraction. Water–SiO_2 nanofluid showed a higher enhancement of the average Nusselt number in comparing to the pure water and water– Al_2O_3 nanofluid. The finding was also revealed that the increasing of the step height increases the reattachment length and thus Nusselt number, the size of the sidewall reverse flow region. (Chen et al., 2006) presented simulations of three-dimensional laminar forced convection adjacent to inclined backward-facing step in rectangular duct, the finding was that the friction coefficient inside the primary recirculation region increases with the increase of the step inclination angle.

The aim of the present work is to investigate the effect of the inclination of the facing step on the heat transfer performance in the backward facing step geometry using Al_2O_3/water as a working fluid and investigate the entropy generation.

DESCRIPTION OF PROBLEM

The problem geometry considered in this work is shown in Figure 1. A channel with a backward facing step with length L1 is considered filled with Al2O3 /water nanofluid. The fluid is assumed to be Newtonian, incompressible and there is no slip velocity between the particle and the base fluid. The thermal properties of the nanoparticle and base fluid are presented in Table 1. The step size of backward facing step is h and channel height H and expansion ration (H/h) equal to 1.5 and the bottom length is L2. At the inlet of the channel, a velocity U and a uniform temperature (T = 300 K) are imposed. The downstream length starting from the edge of the step to the exit of the channel is 20H to ensure that the flow is fully developed flow. The downstream bottom surface of the backward facing step is maintained at T=274 K, while the other walls of the channel are assumed to be adiabatic, the outlet is assumed to be outlet boundary condition. These boundary conditions have been previously used by other authors and the present work is an extension in line with those works. L1=1300 mm, L2=800 mm and h=20 mm

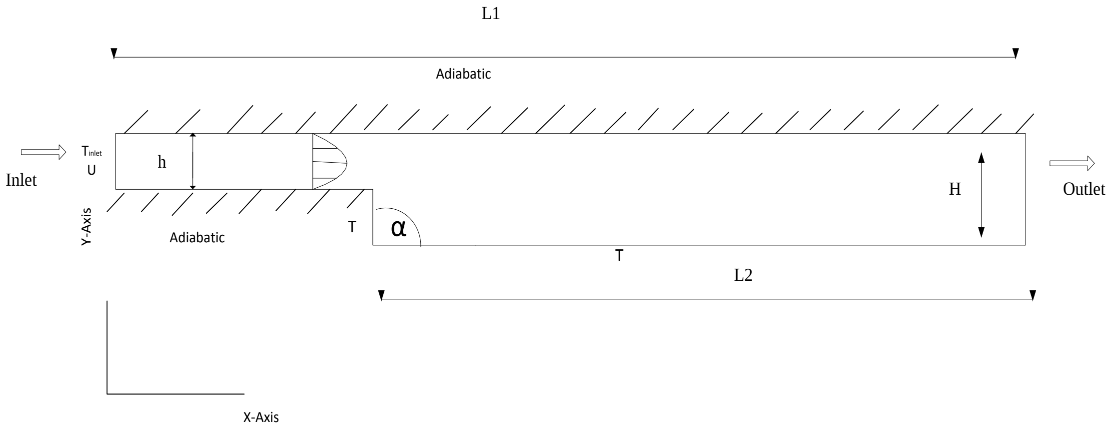

Figure 1 Problem Geometry

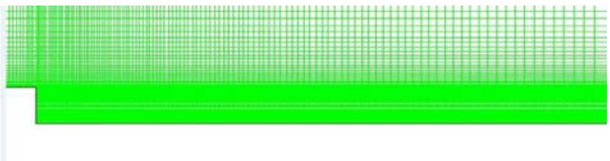

Figure 2 Mesh

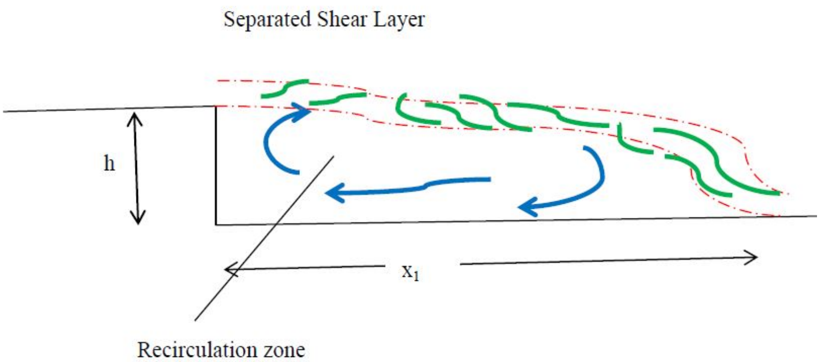

Figure 3 Detailed flow feature of the backward facing flow(Kostas et al.)

Table 1 Thermophysical properties of the base fluid and nanoparticle

Physical property	Base fluid (water)	Al2O3
Heat Capacity(J/Kg K)	4179	765
Density (Kg/m^3)	997.1	3970
Thermal conductivity (W/m K)	0.613	40
Thermal diffusivity α x 10^7 (m^2/s)	1.14	131.7

GOVERNING EQUATIONS AND THERMOPHYSICAL PROPERTIES OF NANOFLUID

The governing equations are continuity, momentum equation and energy equation and can be written as follows

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{v}) = 0 \qquad (1)$$

Momentum equation

$$\frac{\partial(\rho \vec{v})}{\partial t} + \nabla.(\rho \vec{v})\vec{v} = -\nabla p + \nabla.(\tau) + \rho g + F \qquad (2)$$

Energy equation

$$\frac{\partial(\rho E)}{\partial t} + \nabla.(\vec{v}(\rho E + P)) = \nabla.\left(k_{eff} \nabla T - \sum h_j J_j + (\tau \vec{v})\right) \qquad (3)$$

The thermophysical properties of the nanofluid are expressed as

The Nanofluid density

$$\rho_{nf} = (1-\phi)\rho_f + \phi \rho_s \qquad (4)$$

The specific heat of the nanofluid

$$C_{pnf} = \frac{(1-\phi)(\rho C_p)_f + \phi(\rho C_p)_s}{\rho_{nf}} \qquad (5)$$

The effective thermal conductivity was modelled as (Corcione, 2011)

$$\frac{K_{static}}{K_f} = 1 + 4.4 \mathrm{Re}^{0.4} \mathrm{Pr}^{0.66} \left(\frac{T}{T_{fr}}\right)^{10} \left(\frac{K_s}{K_f}\right)^{0.03} \phi^{0.66} \qquad (6)$$

Where k_f and k_s are the thermal conductivity of base fluid and particle respectively

$$\mathrm{Re}_{nf} = \frac{2\rho k_b T}{\pi \mu_f^2 d_p} \quad (7)$$

$k_b = 1.38066 \times 10^{-23}$ J/K is the Boltzmann's constant; d_p is the particle diameter; Pr is the Prandtl number for base fluid and expressed as:

$$\mathrm{Pr}_f = \frac{\mu_f c_{pf}}{k_f} \quad (8)$$

T_{fr} is the freezing temperature for the base fluid.

The viscosity was modelled by (Corcione, 2011) as

$$\mu_{nfststic} = \frac{\mu_f}{\left(1 - 34..87\left(\frac{d_p}{d_f}\right)^{-0.3} \phi^{1.03}\right)} \quad 9)$$

Where dp is the nanoparticle diameter, df is the equivalent diameter of the base fluid and given by:

$$d_f = 0.1\left(\frac{6M}{N\pi\rho_{f0}}\right)^{\frac{1}{3}} \quad (10)$$

Where M is the molecular mass weight of the base fluid, N is the Avogadro number, ρ_{f0} is the mass density of the base fluid calculated at T=293 K

$$h = \frac{q}{(T_H - T_C)} \quad (11)$$

q is the heat flux
h is the heat transfer coefficient

$$Nu = \frac{h.L}{k} \quad (12)$$

$$\mathrm{Re} = \frac{\rho U D}{\mu} \quad (13)$$

Where D is the hydraulic diameter and H is chosen as the hydraulic diameter in this calculations

The entropy is modelled as (Mahian et al., 2013)

$$\dot{S}_{gen}^{'''} = \frac{K}{T^2}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2\right] + \frac{\mu}{T}\left\{2\left[\left(\frac{\partial \nu_x}{\partial x}\right)^2 + \left(\frac{\partial \nu_y}{\partial y}\right)^2\right] + \left(\frac{\partial \nu_x}{\partial y} + \frac{\partial \nu_y}{\partial x}\right)^2\right\} \tag{14}$$

NUMERICAL PROCEDURE

In the present work the conservation equation (1 to 3) are solved numerically using finite volume scheme, the Ansys Work bench 15 package was sued. A source code written in C language was developed to introduce the thermophysical properties of the nanofluids as a user defined function. The geometry was created using ANSYS Workbench design modeler, the mesh created using ANSYS Mesh. Explicit relaxation factor 0.75 for momentum and pressure, standard for pressure spatial discretization. A convergence criterion of $1X10^{-6}$ is chosen for continuity, x-velocity and y-velocity, refined mesh is adopted in the near wall region as shown in Figure 2. A grid independence test was carried out and 24x1200 grid, 36 x 1385 grid and 48x 1620 were tested. The average Nu for these cases was 4.89, 4.92 and 4.93. Hence the final calculations were obtained with 36X 1385.

SIMULATION VALIDATION

This simulation is validated by comparing the present results with experimental results from Armaly for Re=800 and other numerical published results as shown in Table 1. The present results have good agreement with the other numerical results. However, most of the numerical published works, including the present work, underestimate the reattachment length. According to Armaly et al the flow at Re = 800 has three dimensional features, this features arises when using Reynolds number equal to or greater than 400. The reason for the underestimation of x_1 (as shown in Fig. 3) and x_2 which are the reattachment lengths for first and second circulation zones respectively is the assumption of the two-dimensional assumption by all numerical published data.

Table 2 Simulation Validation

Authors	Work Type	x_1	x_2
Armaly	Experimental	7.2	5.3
Vradis	Numerical	6.13	4.95
Pepper	Numerical	5.88	4.75
Abu-Nada	Numerical	6.03	4.81
Present simulation	Numerical	5.94	4.79

RESULTS AND DISCUSSION

The effect of inclination angle α of the face step using nanofluid is investigated numerically and the results of this effect is shown in Figure 4, four angles of facing step is investigated 90°, 97.5°, 105° and 115°. The increase in angle of the face step was found to decrease Nu number and hence the heat transfer rate, the angle 90 was found 4% higher, it is clearly seen that on the bottom wall Nu number has the peak value at the reattachment of Nu is in the separation region where the generated recirculation flow. The flow in the separating region is impinged on the stepped wall and it is responsible for developing the peak values in Nusselt number. As a result of adding the nanoparticle to the base fluid the thermal conductivity is increased and this is the reason for the reduction in temperature gradient at the bottom wall, developing in thermal conductivity is accompanied by developing in thermal diffusivity. The surface Nu number on the bottom wall increases linearly from zero (just before the bottom wall) up to a peak value which lies in the circulation zone(coincide with the point of reattachment), after this point the value of Nu decreases due to the temperature gradient decreases. It is clearly seen that the four angles 90, 97.5, 105 and 115 have identical variation of Nu umber in the bottom wall except in the circulation zone, where 90° angle of face step has the higher Nu number. The reason for this is the change of the shear stress in this area as well as the thermal diffusivity is pronounced in the circulation zone.

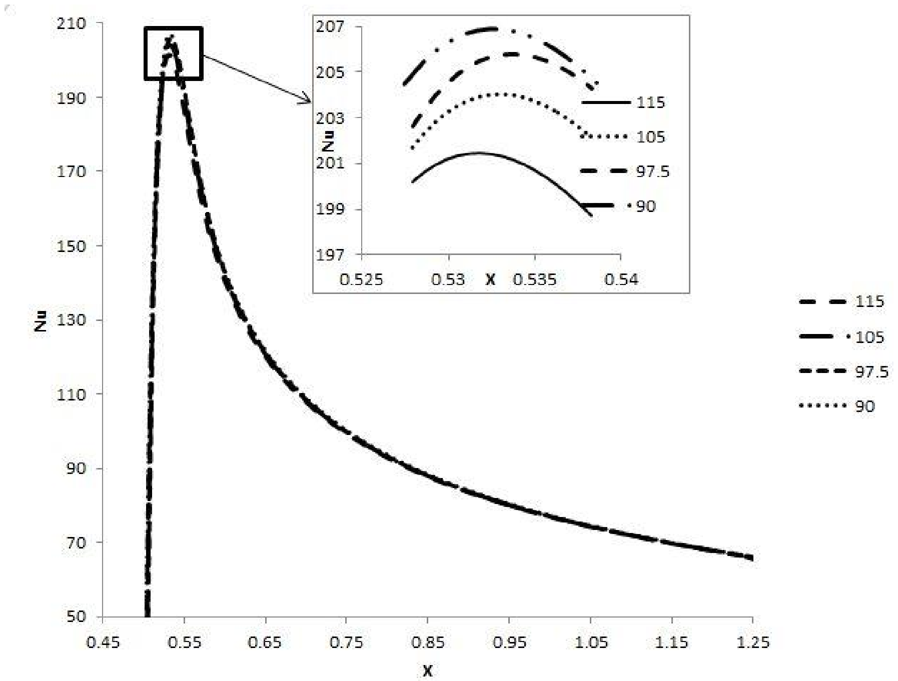

Figure 4 effect of inclination angle on the heat transfer rate

The entropy is also investigated for Re number 40, 100 and 150 for $\alpha=90^o$ and volume fraction 2%. The results are presented in Fig 5. As shown in equation (13) entropy is a function of thermal conductivity and viscosity, these two thermal properties are the most important properties among nanofluid thermal properties. Entropy generation determines the level of the gained irreversibilities during a thermal process. Therefore, entropy production can be employed as a measure to evaluate the performance of engineering devices. For proper optimization of engineering systems in terms for operation and design, the entropy has to be minimized as well as maximizing the heat transfer. It is clearly seen that the increase in Re number results in decrease in entropy, this change is in a good agreement with results in Figure 5 (will be discussed later) which implies that increasing Re number has an advantage of enhancing the heat transfer rate. Re number 150 has minimum entropy compared with Re 40 and 100, the minimum value of the entropy is noted in the circulation zone, the entropy decreases with Re number up to circulation zone and has the minimum value at 0.352 m from the corner of the geometry, i.e. coincides with the reattachment point. The same trend applies to 100 and 40 Re numbers, the only change is the point of the minimum entropy, the explanation for this is that decreasing Re number will result in decreasing the reattachment length which was one of the findings from (Armaly et al., 1983) experimental work.

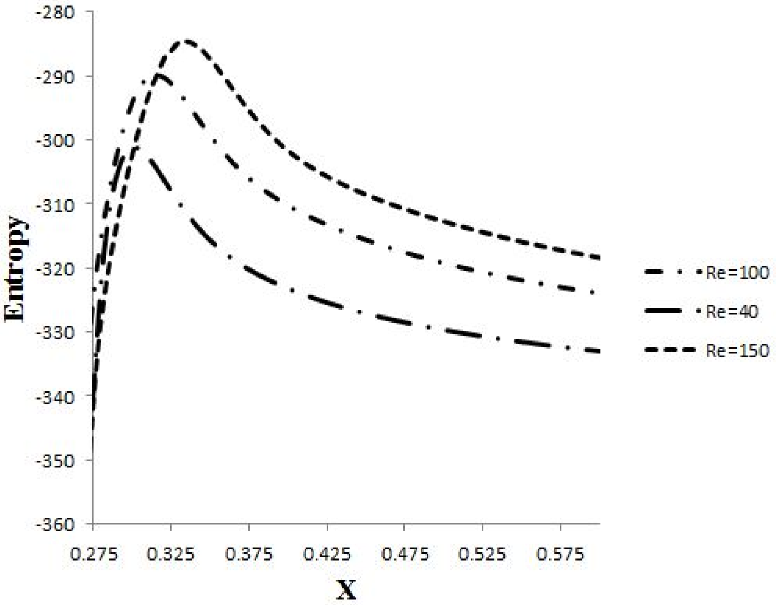

Figure 5 effect Re on the entropy on the bottom wall

The effects of the Re number on the surface Nusselt number in the bottom surface for the laminar ranges are depicted in Fig 6. The increase in Re number increases Nu number along the bottom surface, three Re numbers are investigated 40, 100 and 150, where the substantial compression of thermal boundary layer exist (Kumar et al 2014) the Nu number has a maximum value. Increasing Re number results in increasing in inertia force and increase in thermal conductivity and subsequently an enhancement in Nu number, Re number is also increased by minimizing the viscous forces, using nanofluid may result in increasing the viscosity of the fluid, the increase is very small compared to the develop in the thermal conductivity and hence the inertia force amplifying is the pronounce.

The increase in the Re number has a peak value of Nu umber in the reattachment point and then decreases linearly, along the bottom wall, as the reattachment length increases with the increase in Re (as discussed previously) so the Peak value of Nu number for Re= 100 lies at a point before the location of the peak of Nu for Re=150

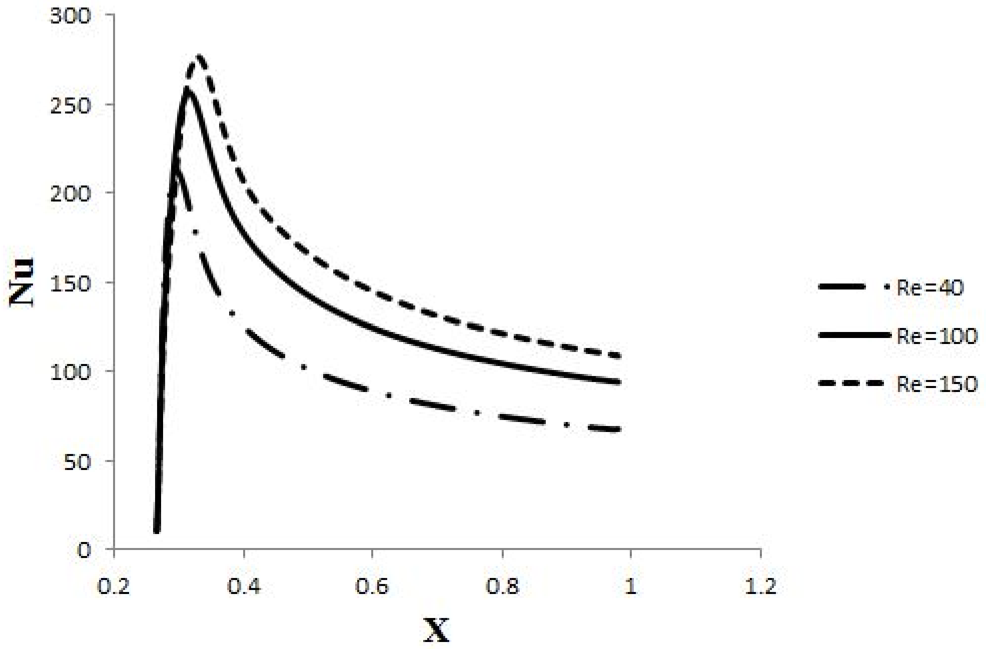

Figure 6 Variation of Nu number for different Re number

The effect of volume fraction on the pressure coefficient is shown in Figure 7. The results show that increasing the volume fraction leads to a slight penalty in the pressure coefficient, the pressure coefficient decreases linearly to the point in which the circulation zone exist, after which the curve increases until the flow passes the circulation zone and drops linearly after that the circulation, the negative sign arises due to the outflow boundary condition at the outlet. In order to ensure the flow is fully developed and to prevent ill-posed. This boundary condition is assumed far from the reattachment point where the diffusion flux for all flow variables in the outlet direction are zero. It is also noted that the three volume fractions 2%, 4% and 6% are almost identical trend before the reattachment point in which the shear stress changes, and far from the circulation zone the more evident the change of these volume fractions.

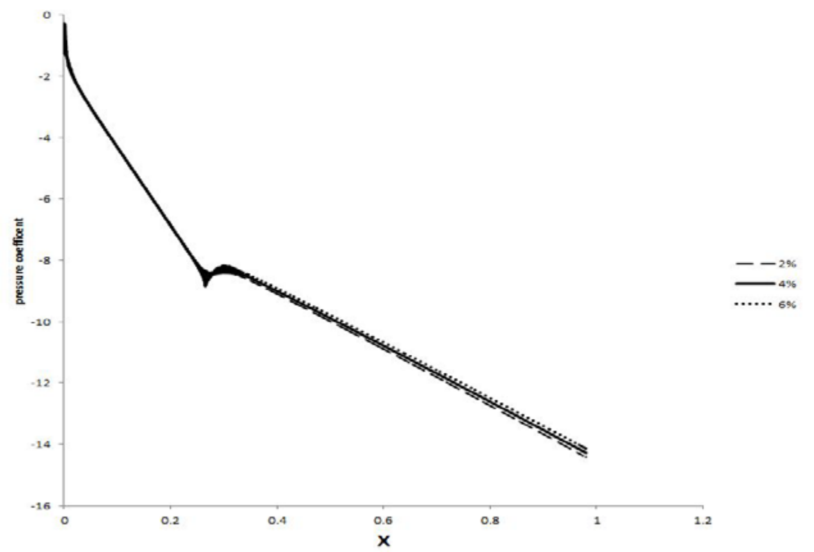

Figure 7 Variation of Pressure coefficent vs vlume fraction

The effective thermal conductivity increase of the nanofluid due to the nanoparticle dispersing is presented in Fig. 8. A comparison of the findings with those of the base fluid (water) is also presented, the results shows that the increase in the volume fraction of the nanoparticle will increase the thermal conductivity of the nanofluid. This increase is due to the high thermal conductivity of the nanoparticle compared to the base fluid as stated in Table1. This increase in thermal conductivity is the main cause of the increase in the heat transfer rate in the system, it is evident that the nanofluid has a higher thermal conductivity than the base fluid which is water, i.e. decreasing the volume fraction results in decreasing in thermal conductivity which is expressed in equation (6)

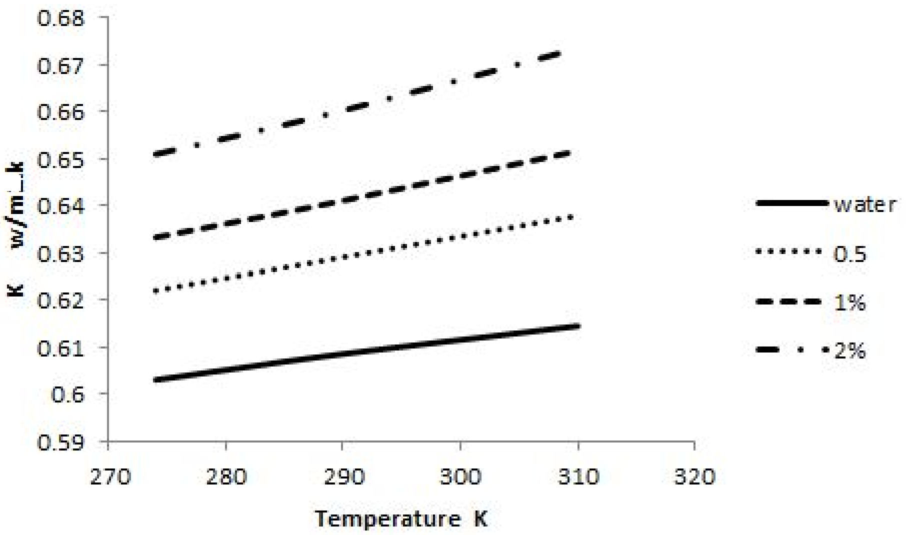

Figure 8 Thermal conductivity enhancement for different volume fractions

NOMENCLATURE

A	Area [m^2]
k	Theraml conductivity [W/m^2K]
Nu	Nusselt number
q''	Heat flux [W/m^2K]
C_p	Specific heat at constant pressure [$Kj\ kg^{-1}\ K^{-1}$]
P_r	Prandtl number
μ	Viscosity [$kg\ m^{-1}\ s^{-1}$]
α	Inclination angle of facing step
H	Downstream channel height [m]
ρ	Density [$Kg\ m^{-3}$]
ϕ	Volume fraction
$S^{///}$	Entropy [$L\ K^{-1}$]
$\dot{Q}$	Heat transfer rate [W]
Re	Reynolds number
T	Temperature [^oK]
h	Heat Transfer Coefficient
L	length [m]
α	Thermal diffusivity[$k/(\rho c_p)$]

Subscripts

eff	effictivt
f	fluid
P	particle
Nnf	nanofluid
H	Hot
C	cold

CONCLUSION

The effect of inclination angle on the heat transfer of laminar Al_2O_3/water nanofluid flow over a backward-facing step was numerically studied. Three nanofluid volume fractions 2%, 4% and 6% were considered at an expansion ratio 1.5 and Reynolds numbers 40,100 and 150 for the laminar regime at a uniform temperature on the wall. Four inclination angles were tested 90^o, 97.5^o, 105^o and 115^o. . The results showed that the increase in the angle decreases the heat transfer rate, 4% enhancement in angle 90^o was found.

REFERENCES:

ABU-NADA, E. 2006. Entropy generation due to heat and fluid flow in backward facing step flow with various expansion ratios. *International Journal of Exergy,* 3**,** 419-435.

ARMALY, B. F., DURST, F., PEREIRA, J. C. F. & SCHÖNUNG, B. 1983. Experimental and theoretical investigation of backward-facing step flow. *Journal of Fluid Mechanics,* 127**,** 473.

BISWAS, G., BREUER, M. & DURST, F. 2004. Backward-Facing Step Flows for Various Expansion Ratios at Low and Moderate Reynolds Numbers. *Journal of Fluids Engineering,* 126**,** 362.

CHEN, Y. T., NIE, J. H., HSIEH, H. T. & SUN, L. J. 2006. Three-dimensional convection flow adjacent to inclined backward-facing step. *International Journal of Heat and Mass Transfer,* 49**,** 4795-4803.

CHOI, S. U. S. & EASTMAN, J. A. 1995. *Enhancing thermal conductivity of fluids with nanoparticles*.

CORCIONE, M. 2011. Rayleigh-Bénard convection heat transfer in nanoparticle suspensions. *International Journal of Heat and Fluid Flow,* 32**,** 65-77.

ERTURK, E. 2008. Numerical solutions of 2-D steady incompressible flow over a backward-facing step, Part I: High Reynolds number solutions. *Computers & Fluids,* 37**,** 633-655.

KHERBEET, A. S., MOHAMMED, H. A., MUNISAMY, K. M., SAIDUR, R., SALMAN, B. H. & MAHBUBUL, I. M. 2014a. Experimental and numerical study of nanofluid flow and heat transfer over microscale forward-facing step. *International Communications in Heat and Mass Transfer,* 57**,** 319-329.

KHERBEET, A. S., MOHAMMED, H. A., MUNISAMY, K. M. & SALMAN, B. H. 2014b. The effect of step height of microscale backward-facing step on mixed convection nanofluid flow and heat transfer characteristics. *International Journal of Heat and Mass Transfer,* 68**,** 554-566.

KOSTAS, D., SORIA, J. & CHONG, M. A study of a backward facing step flow at two Reynolds numbers.

Kumar, Ankit, Dhiman, Amit. 2014. Forced Convection Heat Transfer of Newtonian Fluids from a Backward-Facing Step: Effects of Expansion Ratio, Reynolds, and Prandtl Numbers. Heat Transfer -Asian Reasearch

LAN, H., ARMALY, B. F. & DRALLMEIER, J. A. 2009. Three-dimensional simulation of turbulent forced convection in a duct with backward-facing step. *International Journal of Heat and Mass Transfer,* 52**,** 1690-1700.

MAHIAN, O., KIANIFAR, A., KLEINSTREUER, C., AL-NIMR, M. D. A., POP, I., SAHIN, A. Z. & WONGWISES, S. 2013. A review of entropy generation in nanofluid flow. *International Journal of Heat and Mass Transfer,* 65**,** 514-532.

MOHAMMED, H. A., AL-ASWADI, A. A., ABU-MULAWEH, H. I. & SHUAIB, N. H. 2011. Influence of nanofluids on mixed convective heat transfer over a horizontal backward-facing step. *Heat Transfer-Asian Research,* 40**,** 287-307.

MOHAMMED, H. A., ALAWI, O. A. & WAHID, M. A. 2015. Mixed convective nanofluid flow in a channel having backward-facing step with a baffle. *Powder Technology,* 275**,** 329-343.

POUR, M. S. & NASSAB, S. A. G. 2012. Numerical Investigation of Forced Laminar Convection Flow of Nanofluids Over a Backward Facing Step Under Bleeding Condition. *Journal of Mechanics,* 28**,** N7-N12.

TOGUN, H., SAFAEI, M. R., SADRI, R., KAZI, S. N., BADARUDIN, A., HOOMAN, K. & SADEGHINEZHAD, E. 2014. Numerical simulation of laminar to turbulent nanofluid flow and heat transfer over a backward-facing step. *Applied Mathematics and Computation,* 239**,** 153-170.