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Study the Effect of Inclination in Micro Fluidization Beds on Hydrodynamics Parameters

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ABSTRACT

In this paper, the micro fluidized bed investigated numerically at various bed inclination angles. Micro-fluidized beds are widely used in laboratories to improve and enhance the efficiency of fluidized beds in industries. Thus, ensure that the properties of large FBs are applicable upon implementation. CFD simulations are conducted using Ansys Fluent Software Program 2022R2. The effects of bed inclination on various model parameters were investigated. The investigation focused on analysing the pressure drop during the fluidization process at four different bed angles: 2, 6, 8 and 10 degrees. Additionally, the study explored the effects of inclination on turbulent viscosity, effective viscosity, turbulent kinetic energy and volume fraction of solid. The findings indicated that the pressure drop showed variations (decrease and increase) with time, turbulent and effective viscosities increased then decreased with inclined angles at different water velocities. Turbulent kinetic energy grew with increasing water velocity; however, the volume fraction of solids remained stable.

1. INTRODUCTION

Fluidized beds theory depends on relationship between two or three phases like solid-liquid, solid-gas or solid-liquid-gas depends on principles of mass, heat, and fluid transfers that used in many practical and commercial industries reactors, evaporators, gasification, solid drying etc. The knowledge and tools of managing and treating fewer volumes of fluids in tubes with diameters on the range of many tens or many hundreds of micrometres is known as microfluidics [1]. This study area has potential applications in the fields of medical diagnostics and the automation of chemical and biochemical analysis and processing. However, because the flows in conduits of this size are usually laminar, molecular diffusion dominates the transport process. This forms a significant hurdle to the application of microfluidics in many domains where transport plays a significant role, such as micro-reactors, which offer an evangelist means of achieving process intensification [2].

Very few works have been concentrated on inclined micro fluidized bed. Zhang et al. [3] examine the hydrodynamics of water-particle MFB under the effects of bed inclination and various solid-to-channel diameter combinations. They confirmed for the inclination of the micro-fluidized bed increasing from 0 to 10 degrees.

Examination of the behaviour of the bed showed a distinct pattern of reduced bed expansion for every combination of particle-to-channel diameter, with an increase in the inclined bed.

Cúñez and Franklin [4] used experimental and numerical tools to measure the movements of individual particles during layer inversion in small pipes. They found that particles traverse distances during the inversion and that the characteristic period for layer inversion occurs.

In the instance of very narrow tubes, Cúñez and Franklin [5] investigated the crystallization and jamming that occur at liquid velocities higher than that of the initial fluidization in solid-liquid fluidized beds. When the water flow slowed down to a velocity that was still higher than what was required for bed fluidization, they discovered that the particles had crystallized.

Cúñez et al. [6] contrasted simulations for beds made up of duos and trios of bonded aluminium spheres with experiments to study the dynamics of solid–liquid fluidised beds of bound spheres in extremely thin tubes. They found that when the water velocity increases, the specific length of the tube diameter for plug formation, which occurs for both duos and trios—decreases. This phenomenon is comparable to loose sphere observations, in which individual components move throughout the entire bed. Gao et al. [7] performed kinetic models of the pyrolysis of three Iranian waste oils in a micro-fluidized bed. They demonstrated an ideal value for the reaction rate and demonstrated that the two most crucial parameters for the maximum fuel conversion level are the temperature and pace of the reaction.

By altering the particle diameter, density, and bed angle with respect to the horizontal plane, Khurram et al. [8] investigated transport velocity in an inclined fluidized bed.

Guo et al. [9] studied the fluidization behaviours of micro-fluidized beds. They found that the pressure drop was less than that calculated from Ergun equation and that the voidage decreased with an increase bed diameter. Additionally, they looked into how the size distribution and particle characteristics affected the lowest velocityUsing the CFD model created in the earlier work, Luo et al. [10] provided a numerical study on hydrodynamics in liquid-solid circulating fluidized beds under a variety of operating conditions, including different superficial liquid and solid velocities, particle densities, and shapes. Their numerical predictions matched the experimental data well and were made with an accurate procedure.

According to Qie et al.'s study [11] of the features and uses of micro fluidized beds, many authors have described the micro fluidized bed. Gas-solid (GS), liquid-solid (LS), gas-liquid-solid (GLS), and other MFBs with special structures, like membrane-assisted (MAMFBs) and micro circulating MFBs (MCFBs), are categorized in this review. Based on existing research, it provides an overview of the description and properties of MFBs and looks at how wall effect, cohesive force, and adhesion force affect MFBs' minimum fluidization velocity (Umf) and hydrodynamic characteristics. Furthermore, MFB applications are explored in relation to assessing fast reactions and extracting kinetics that are near to the intrinsic ones.

Zivkovic et al. [12] studied the differences between micro-fluidized system experiments and traditional fluidized system equivalents. When constructing the μFBs, they discovered that the surface forces are of the utmost importance whereas particle adhesion to the walls delays fluidization. When they compared the behavior of μFBs with the standard fluidization equations, they found that these equations are still suitable for the construction of such FBs.

Based on experimental data, Li et al. [13] investigated the development behaviour of micro fluidized beds and discovered that it differed significantly from that of conventional fluidised beds. The expansion ratio of the micro-fluidized beds reduced as the stabilised liquid velocity increased. The greatest number of particle configurations and the radial direction of particle motion are affected by the wall effect in micro-fluidized beds, which rises as the particle-to-bed diameter ratios increase. Larger local voidage and an increase in the expansion ratio result from this.

A fluidised bed column's characteristics can be naturally changed by tilting it by 1.5 degrees, as demonstrated by Del Pozo et al. [14]. The particle-liquid mass transfer and heat-transfer coefficients can both increase by up to 30%, however the gas-liquid mass-transfer coefficient can only vary by up to 15Vo in bed analysers.

Ridha and Ch [15] examined the fluidized bed in an inclined station. Different water velocities, solid particle heights, and inclination angle values were employed. Using CFD, the investigation was carried out numerically. It was discovered that the amount of solid particles inside the pipe increased as water velocity increased, and as the pipe's slant grew, the expansion of the solid particles reduced.

Through testing, Yakubov et al. [16] examined the dynamic and structural characteristics of fluidized bed inclined pipes. They investigated the effects of altering the inclination angle of the pipe on the fluidization process. Their studies showed that in columns inclined at a 45-degree angle, the essential flow rate for bed escape reaches its maximum. The first bed breaking up into numerous secondary beds, resulting in a concentration wave pattern, typifies the fluidization process in these inclined columns. The particle density and diameter are increased by this procedure. Additionally, their investigations showed that the critical flow rate is mostly independent of column length.

Jiang et al. [17] examined the impact of inclination angle on the thermal functioning of a three-phase closed thermosyphon containing SiC particles. The highest decreasing rates of overall thermal resistance were determined to be 32.9%, 26.7%, 37.0%, and 30.5%, respectively, for the inclination angles of 0°, 10°, 20°, and 30°. Depending on the solid holdup, the maximum decreasing rates of the overall thermal resistance exist at low input power.

In this work, we investigated micro fluidized bed with different inclined angles using Ansys Fluent 2020R2. The model was validated by another investigation.

2. METHODOLOGY

2.1 General equations

The Eulerian model was utilized to analyze the solid particle distribution and liquid flow within the bed. The mass and energy conservation equations can be solved using the Eulerian model (Fluent User's Guide 2006) [18]. The general equations can be listed as below:

Mass conservation equation:

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla \cdot \left(\alpha_q \rho_q v_q\right) = \sum_{p=1}^{n} \left(\dot{m}_{pq} - \dot{m}_{qp}\right) + s_q \quad (1)$$

Conservation of Energy equation:

$$\begin{aligned} &\frac{\partial}{\partial t}\left(\alpha_q \rho_q h_q\right) + \nabla \cdot \left(\alpha_q \rho_q u_q h_q\right) \\ &= -\alpha_q \frac{\partial p_q}{\partial t} + \bar{\tau}_q : \nabla u_q - \nabla \cdot q_q + s_q \\ &+ \sum_{p=1}^{n} \left(Q_{pq} + \dot{m}_{pq} h_{pq} - \dot{m}_{qp} h_{qp}\right) \end{aligned} \quad (2)$$

2.2 Boundary conditions

From Zhang et al. [3], the boundary conditions taken for validation involved operating the fluidized bed for two-phase flow (liquid- solid). The fluidized bed was inclined at four different angles: 2, 4, 8 and 10 degrees. The details of the boundary conditions are presented in Table 1.

Table 1. Boundary condition's description

Description	Value
Bed length L	0.1 m
Bed diameter D	4×10^{-3} m
Particles diameter dp	8.5 μm
Density of solids	2460 kg/m^3
Density of liquid	998 kg/m^3
Initial height of static bed	3×10^{-3} m
Liquid velocities	(0.0005, 0.003, 0.0045, 0.006) m/s
Maximum number of iterations	20
Condition of outlet boundary	outflow
Time steps	0.001 s
Convergence criteria	0.001
Element size	1×10^{-4} m

2.3 The model's mesh

2.3.1 Grid independence test

Grid size has an influence on the accuracy of CFD investigation. A lesser grid size generally provides more accurate findings than a larger grid size, but it requires more time and more power [19, 20]. For this simulation, the Multizone Quad/Tri method was used. To obtain suitable grid results, the number of elements was calculated depends on the error percentage. The test was performed to determine the pressure at point 1 in Figure 1 at time 0.1 seconds for inclined bed at 8 degree and 0.003 m/s. A grid with 40,000 elements and an element size of 1×10^{-4} was found to be more suitable for this simulation, resulting in a percentage error approximately 2.152%. Table 2 shows the numbers of rejected and accepted elements.

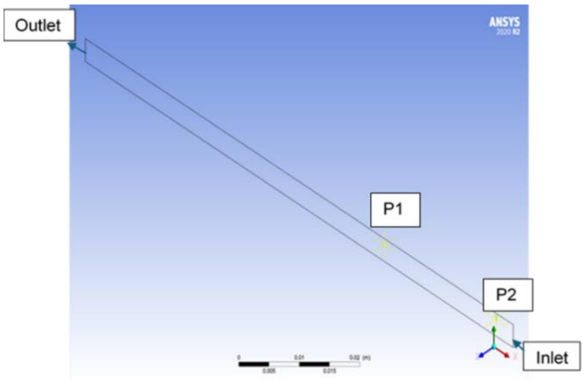

Figure 1. 2D Geometry bed

Table 2. Validation of meshing use

Element's Number	Trail No.	Determined Pressure at Point 1 (pa)	Error Present (%)	Element Size (m)
10000	1	0.929		2×10^{-4}
40000	2	0.949	2.152	1×10^{-4}
49995	3	0.996	4.718	9×10^{-5}
81339	4	1.053	5.722	8.5×10^{-5}

The following equation show how determine the errors:

$$error\ persent\% = \frac{M - A}{A} * 100$$

where, M is the pressure in point 1 in next trail and A is the pressure in point 1 in previous trail.

2.3.2 The mesh conditions

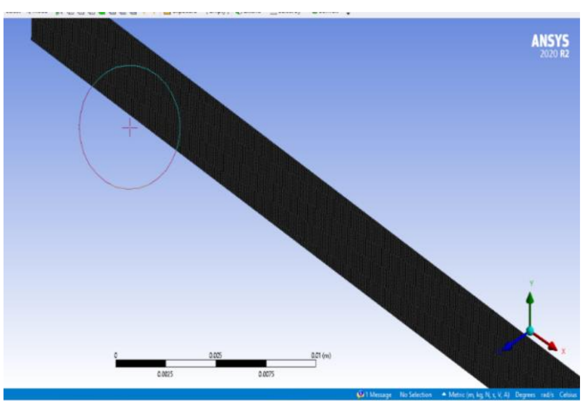

Figure 2. Mesh of model

Ansys fluent CFD software program 2020R2 was used to perform the simulation for this study. The time step size was set to 0.001 seconds, with a total time of 20 time steps per iteration and 600 iterations, repeated until the simulation reached a time of 5 seconds. Figures 2 and 3 show the mesh and magnifier mesh, respectively.

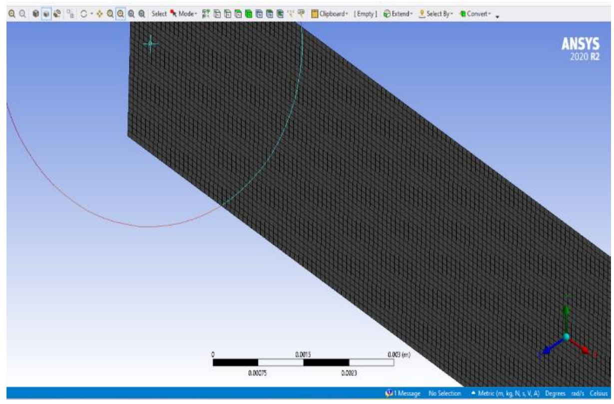

Figure 3. Magnifier of mesh

2.4 Validation of the model

Zhang et al. [3] investigated the liquid-solid inclined micro fluidized bed's hydrodynamics. They studied the effect of inclination bed on bed expansion for different diameters of particles and water velocities. Figure 4 shows the validation of the present study by comprising it with Yi Zhang's study for inclination angles of 2, 6, 8 and 10 degrees. The results clearly show convergence.

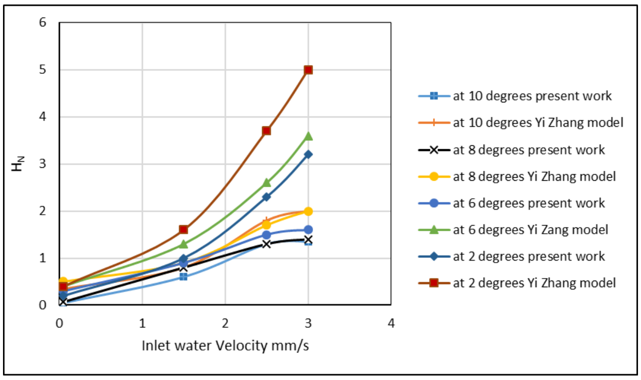

Figure 4. Numerical model's validation

3. RESULTS AND DISCUSSION

3.1 Inclination angles' impact on a simulated pressure drop

Understanding the behaviour of pressure drop is necessary in order to know the fluidized bed's hydrodynamic characteristics. The relationship between pressure drop and bed inclination at various water velocities is depicted in Figures 5-8. The values of pressure drop increases with inclination bed inclination, ranging between 1225 to 4000 Pa. The increase occurs because, as the inclination approaches the horizontal angle, the pressure drop decreases compared to when the bed is closer to the vertical angle, except at 10 degree where the values do not exceed 600 Pa. Generally, the pressure drop values are relatively close to each other, with variations occurring due to the continuous movement of particles during fluidization. This movements are happenend due to incease the amount of water that pushed in bed, it leads to incease in particles into behind places into pipe.

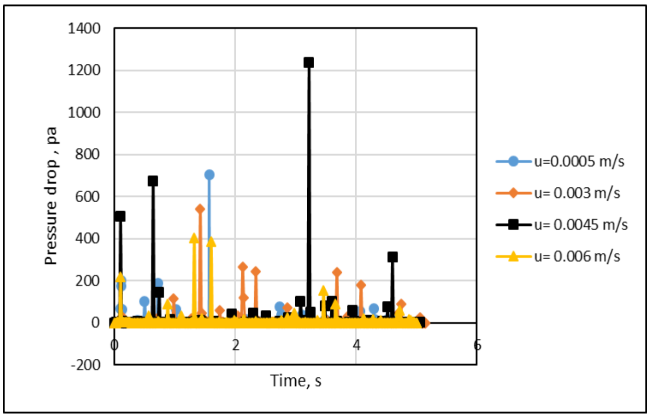

Figure 5. Pressure drop versus time at inclined of fluidized bed 2° with different water velocities

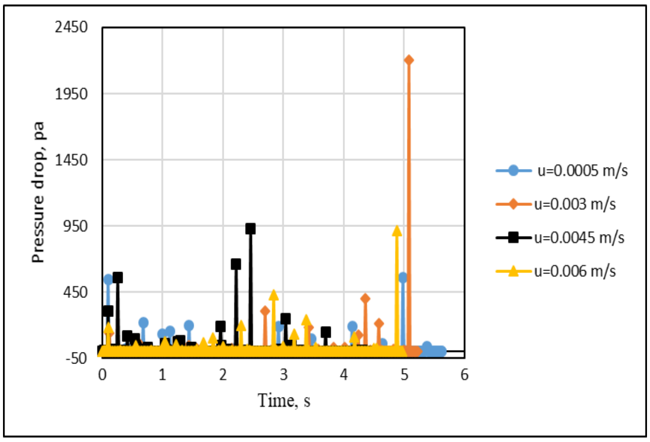

Figure 6. Pressure drop versus time at inclined of fluidized bed 4° with different water velocities

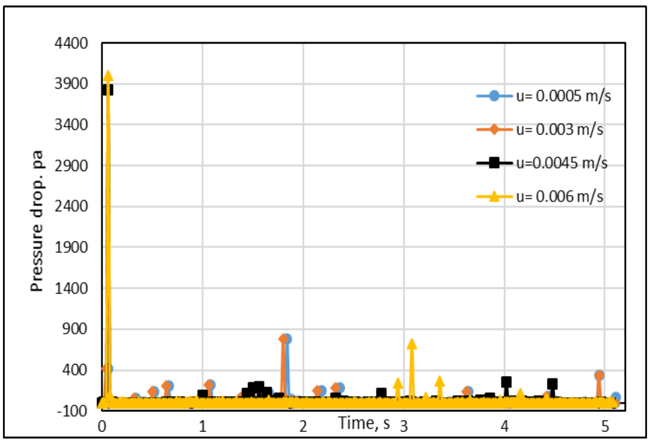

Figure 7. Pressure drop versus time at inclined of fluidized bed 8° with different water velocities

3.2 Effect of inclination of bed on turbulent and effective viscosities at varied water velocity

Figures 9 and 10 represent the turbulent and effective viscosities, respectively, as functions of bed inclination at different velocities. In these two figures, both the turbulent and effective viscosities starts low, increase to a peak and then decrease. This occur because the inclination effect on fluid flow recapture process that was retard in a wake region near the pipe. The greatest values are noted at a velocity of 0.003 meters per second, while the maximum values are seen at an inclination angle of 8 degrees.

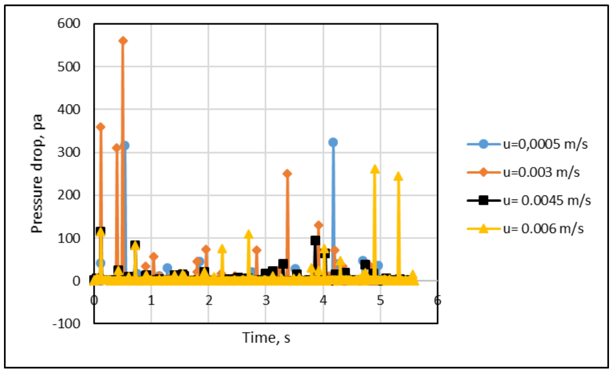

Figure 8. Pressure drop versus time at inclined of fluidized bed 10° with different water velocities

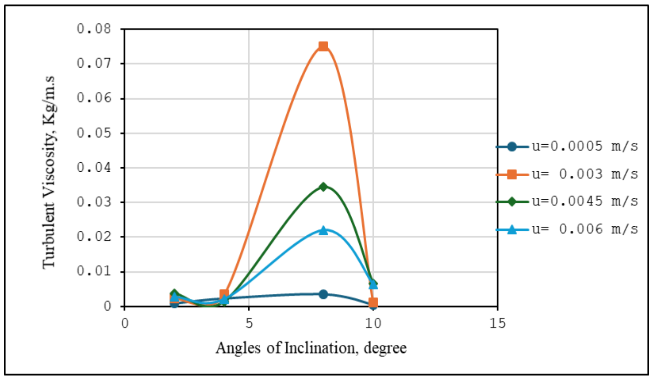

Figure 9. Turbulent viscosity of inclined fluidized bed with various inlet velocity of water

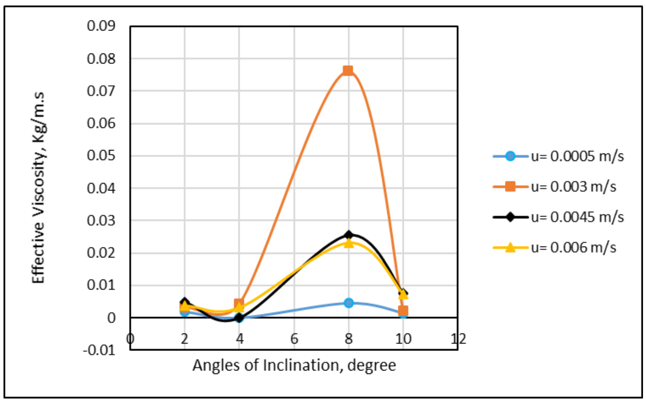

Figure 10. Effective viscosity of inclined fluidized bed with various inlet velocity of water

3.3 Effect of inlet water velocity on turbulent kinetic energy at different degrees of inclination

Figure 11 shows the relationship between turbulent kinetic energy and inlet water velocity at different bed inclination angles. The figure indicates that turbulent kinetic energy increases with increase velocity, except at an angle of 4 degree, from this figure. It can see that the arrangement of inclination degrees of bed doesn't affect much on the relation between turbulent kinetic energy and inlet velocity because the friction resistance of column's wall that is the main reason of turbulent of flow around the pipe where the presence of eddies affects the trend during the fluidization.

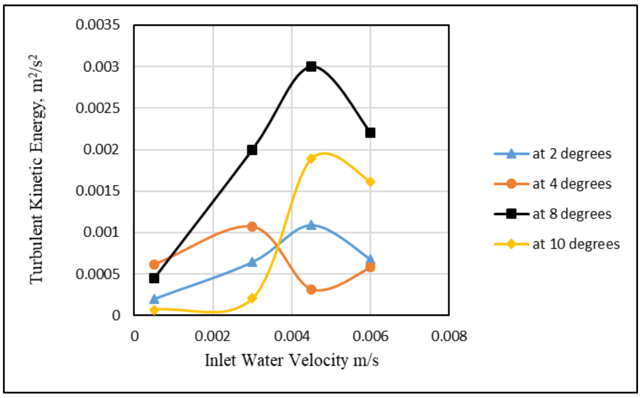

Figure 11. Turbulent kinetic energy versus inlet water velocity at various degrees of inclination

3.4 Inlet water velocity's influence on solid volume fraction at different degrees of inclination

In the simulation of the present study, the volume fraction of solids remains similar across different water velocities at various bed angles, as shown in Figure 12. This observation indicates that the water velocity does not have a significant effect on the volume fractions.

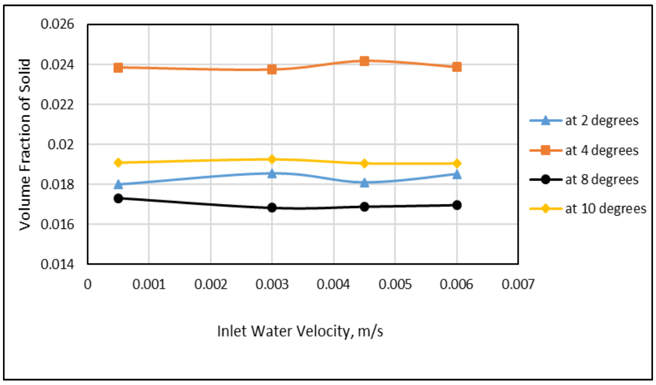

Figure 12. Volume fraction of solid versus inlet water velocity at various degrees of inclination

4. CONCLUSIONS

In this paper, the micro- fluidized bed was investigated at various bed inclination angles. CFD simulations were used to investigate the effects of bed inclination on various model parameters.

The model was validated by experimental results from a previous study. The main findings are as follows:

1. The pressure drop exhibited fluctuations but remained relatively consistent over the simulations, this occur in one angle of inclination. In addition, the results showed that pressure drop increase with increase in inclination with neglecting the direction of inclination and with small sizes of beds.
2. Turbulent viscosity and effective viscosity both increased and then decreased with increasing in inclination of beds and water velocity.
3. Turbulent kinetic energy increased with upgrading water velocity, while the volume fraction of solid remained approximately stable.

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NOMENCLATURE

A	Volume fraction
B	Dimensionless heat source length
CP	Specific heat, J. kg^{-1}. K^{-1}
D	Diameter (m)
E	Rib height (m)
F	Force (N)
g	Gravitational acceleration, $m.s^{-2}$
k	Thermal conductivity, $W.m^{-1}$. K^{-1}
h	Heat transfer coefficient ($w/m^2.K$)
Nu	local Nusselt number along the heat source
Pr	Prandtl number (μCp/k)
Re	Reynolds number (ρ u D/μ)
T	Temperature (K)
v	Velocity (m/s)
w	Duct width (m)

Greek symbols

α	Thermal diffusivity, m^2. s^{-1}
β	Thermal expansion coefficient, K^{-1}
ϕ	Solid volume fraction
Θ	Dimensionless temperature
μ	Dynamic viscosity, kg. m^{-1}. s^{-1}