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CFD Analysis of Porous Medium Burner for Domestic Cooking Application

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Abstract

Background/Objectives: Porous medium burners are presented as an alternative technology in order to improve the thermal efficiency and emission characteristics of domestic cooking stoves. In this paper CFD analysis of a 90mm top diameter porous medium burner (PMB) which is made of two different sections, namely pre-heating and combustion section is considered. **Methods/Statistical Analysis:** Silicon carbide foam having a thickness of 25mm and 10ppi porosity in the combustion section and 6.5mm diameter steel balls in pre-heating section was used. The variation in the model was due to different measurement values of centre pipe length and fluid inlet diameter. The centre pipe length was 27.5mm, 55mm, 110mm and 220mm each, whereas the fluid inlet diameter was 15mm, 20mm and 25mm. The mass flow rate of air and fuel were 0.05kg/m^3 and 0.009kg/m^3 with temperature of air 300k and fuel 285k respectively. Wall temperature was taken as 300k and 5% turbulence intensity at all inlet and outlet. Air and LPG are used as oxidizer and Fuel. **Findings**: ANSYS Fluent was used to simulate the mixing and reaction of Fuel and Oxidizer through a two layer porous burner. The burner was evaluated considering turbulence model and Species Model. Total six 3D models are considered for simulation and results are taken as Contours of Temperature. It was found that porous burner having centre pipe diameter of 27.5mm and 25mm fluid inlet diameter gives the maximum surface temperature of 2250k. Increasing the centre pipe length by half (27.5mm – 55mm) caused a slight drop of surface temperature which is almost negligible. Furthermore, from the temperature contours, it was observed that increasing the center pipe length above 55mm reduced the surface temperature by 300k. From the four models considered the minimum surface temperature was 2087k, for porous burner model having 110mm centre pipe length and 25mm fluid inlet diameter. Based on the insight obtained from the CFD simulation, increasing the center pipe length above the range of 27mm to 55mm, might increase the chance of flashback. Considering the fluid inlet diameter, increasing the fluid inlet diameter by 5mm caused an increase of surface temperature by about 300k. **Improvements/Applications**: Porous medium combustion has been center of interest amongst researchers due to its higher thermal efficiencies and lower emission of Nox and CO gases. They are employing a porous media for various applications, such as: IC engines, heat exchangers, gas turbine and propulsion, hydrogen production and cooking applications.

Keywords: Computational Fluid Dynamics (CFD), Cooking Application, Porous Burner (PB), Porous Medium Combustion (PMC), LPG

1. Introduction

In developing countries Energy used for cooking application represents a considerable portion of the total energy requirement. Nowadays, household liquefied petroleum gas (LPG) cooking stoves are well known and are used for various domestic and commercial purposes. Considering the increasing growth rate usage, it is vital to make some improvement on the performance of standard burners to increase efficiency with overall positive impact on the economy and environment. In standard burner the combustion is characterized by a free flame where the heat transfer is mainly by convection. As gases are known with poor heat conductivity and reduced opacity, role of

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conduction and radiation modes of heat transfer is negligible. In recent years, porous medium combustion (PMC) has received special attention due to its higher thermal efficiencies, lower nitrogen oxide and carbon monoxide emissions, high burning velocity, high flame speed, wider flammability limit, reduced temperature drop across the reaction zone and high radiant output. In this paper computational fluid dynamics (CFD) modeling and analysis of porous medium burner for domestic cooking application is considered. It is evident from the literature that most of the reported work on porous media burner for domestic cooking application is based on experimental approach and there is a lack of computational fluid dynamics (CFD) studies. The performance of two different shape porous burners namely, straight and divergent with diameters 90 millimeter and 70 millimeters, and divergent shape burner having diameters 90 millimeter top and 70 millimeter bottom. Liquefied Petroleum Gas was fuel of choice and 79% was the maximum efficiency for 90 millimeter diameter porous burner at equivalence ratio of 0.491[1]. A porous radiant burner has been developed and tested for domestic cooking application. Porous burners of different porosity were examined at different equivalence ratio and wattage. Maximum thermal efficiency of 75% was obtained, which is 10% higher thermal efficiency than the maximum thermal efficiency of a conventional LPG burner[2].

An extensive research work has been carried out to improve the thermal efficiency of SPMB by introducing PM technology and using Liquefied petroleum gas as a fuel source. The thermal efficiency of conventional gas burner and self-aspirating porous medium burner increased indirectly with the decrease in the firing rate between 21 to 44Kw. The same increasing effect was observed by varying the distance from top to bottom of the vessel between 75 to 125 millimeters[3]. The combustion behavior of a domestic cooking stove has been tested numerically and experimentally by introducing a two layer porous material and an LPG fuel source. A pre heating zone of material alumina balls matrix as well as a combustion zone made of silicon carbide matrix with 90% porosity were examined numerically by using FVM. The effect of silicon carbide matrix thickness, the thickness of the pre heater, scattering albedo and conductivity of the solid phase were also studied[4]. The performance of porous radiant burner for cooking application was investigated for power capacity not more than 10KW. A silicon carbide based porous burner of diameter 120 millimeters and porosity of 90% were used to investigate the effect of different power inputs (5–10KW) on the thermal efficiency as well as the emission levels. It was found that silicon carbide based porous radiant burner gives maximum efficiency of about 50%[5].

A two layerself aspirating porous burner was developed to study the heat transfer behavior for domestic cooking application. The experimental result showed that the homogeneous porous media might give off, emit and scatter thermal radiation in addition to its convective heat exchange with the gas. Due to the combined effect of convection and radiation the rate of heat transfer was found to be higher at the centre of the porous burner with maximum thermal efficiency of 64%[6]. The feasibility of porous burner technology was examined using the commercial fluid dynamics code ANSYS CFX to study the relationship between the porous solid and the fluid and also to accurately assess the combustion behaviors. Sic foam of 81% porosity with methane as a fuel source. It was observed that the combustion behavior is directly affected by the energy balance within the system and exhibited behavior characteristic of porous burner[7]. A numerical scheme has been developed to examine the thermal performance of porous media burner (PMB) using the finite volume method (FVM). 2D navier stokes, energy and chemical species transport equations were solved and heat release was described by a multiple step kinetics mechanism. The FVM was also used to work out the radiation heat transfer equation, to compute the local radiation sources. The paper concluded that temperature profile, fuel velocity and convective heat transfer were significantly affected by parameters such as excess air ratio, conductivity and radial properties of the solid material and heat transfer coefficient[8]. An experimental investigation has been carried out to study the performance of conventional burner by using different porous media. A maximum thermal efficiency of 61% was obtained for metal ball based porous burner which shows a 10% better thermal efficiency than conventional burners[9]. The performance of radiant shape metal porous burner was studied by measuring the surface temperature at different equivalence rations and firing rates. The burner was operated for five different firing rates; 98 kW/m^2, 196 kW/m^2, 294kW/m^2, 392 kW/m^2 and 490 kW/m^2. A maximum thermal efficiency of 30% was obtained in three layer wire mesh porous burner. The temperature at the surface of the burner increases with increasing firing rate[10].

A new burner design was proposed to improve the thermal efficiency of conventional domestic stoves by introducing a porous medium technology. The experimental result showed that PM was very effective in improving the thermal efficiency due to internal heat recirculation. The proposed porous radiant re-circulated burner (PRRB) has a maximum thermal efficiency of 10% which is better than conventional burner[11].

2. Computational Technique

2.1 Porous Burner Geometry

The Basic model considered for simulation is 90mm top diameter porous burner. Different variations of model are created by changing fluid inlet diameter and Centre pipe length. Figures 1,2 shows a schematic diagram of two layer porous burner consisted of two sections i.e. preheating and combustion section. In this computational analysis Combustion section was treated as a silicon carbide ceramic foam having 10ppi and thickness 25 mm. Preheating zone is filled with steel balls having diameter 6.5 mm each. Air fuel mixture, first preheated in the preheating zone then combustion takes place in the combustion zone. Heat is transmitted in all the directions by the conduction, convection and radiation modes of heat transfer.

2.2 Computational Mesh

While performing any numerical analysis of complex processes the computational mesh generation is an important procedure, (Figure 3,4). For complex geometries generating a suitable mesh can be quite challenging. ANSYS workbench meshing has several options and tools to aid in the generation of high quality mesh. To generate a computational mesh the model was divided in to five named selections. Inlet air, inlet fuel, outlet, mesh material and wall. A hexahedral mapped mesh (Figure 4) and a tetra/pyramid free mesh type with a multi-zone method is used for meshing and the steps adapted are given in Table 1,2.

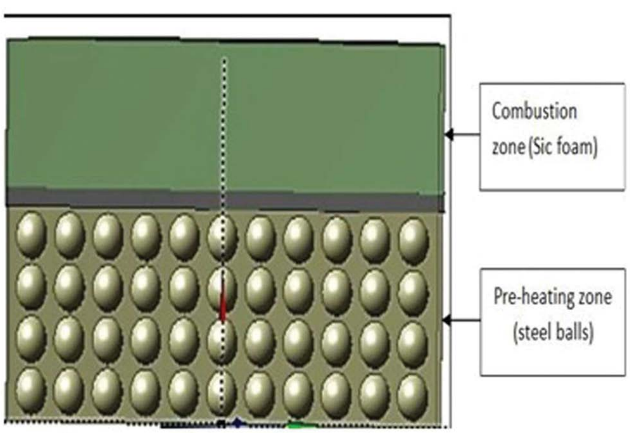

Figure 1. Zones in porous medium.

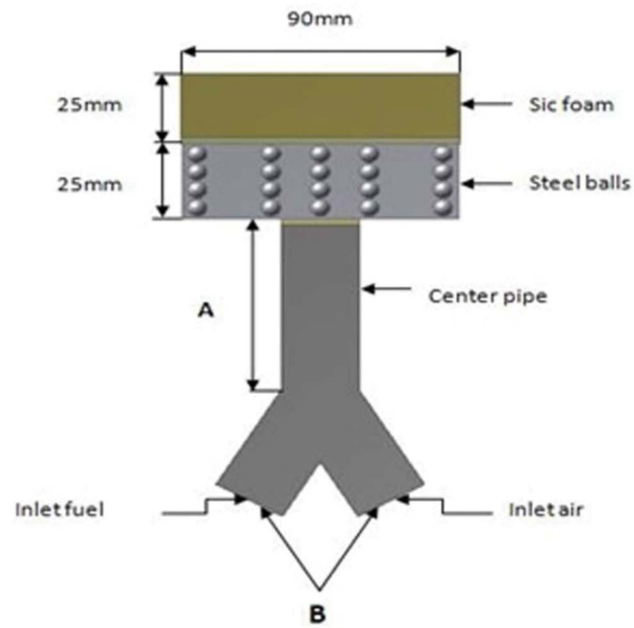

Figure 2. Schematic of two layer porous medium burner.
A = Centre pipe length: 27.5mm, 55mm, 110mm, and 220mm
B = fluid inlet diameter: 15mm, 20mm, and 25mm

2.3 Governing Equations

Continuity equation $$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho U_i)}{\partial x_i} = 0 \quad (1)$$

Momentum equations $$\frac{\partial}{\partial t}(\rho u_i)\frac{\partial}{\partial x_j}\left(\rho u_j u_i - \tau_{ji}\right) + \frac{\partial p}{\partial x_i} = s_i \quad (2)$$

Viscous stress tensor $$\tau_{ii} = -\frac{2}{3}\mu D + 2\mu\frac{\partial u_i}{\partial x_i} \quad (3)$$

$$\tau_{ii} = \mu\frac{\partial u_i}{\partial x_j} \quad (4)$$

Energy equation $$\frac{\partial(\rho h)}{\partial t} + \frac{\partial \rho u_{ih}}{\partial x_i} = -\frac{\partial p}{\partial t} + \frac{\partial}{\partial x_i}[\frac{k}{cp}\frac{\partial h}{\partial x_i} - i \wedge R \quad (5)$$

The generalized governing equations for variable φ can be expressed as

$$\frac{\partial}{\partial t}(\rho \varnothing) + \frac{\partial}{\partial x_j}\left(\rho u_{j\varnothing} - \frac{\Gamma_\varnothing}{\sigma_\varnothing}\frac{\partial \varnothing}{\partial x_j}\right) = S_\varnothing \quad (6)$$

$$\frac{\partial(\rho\varnothing)}{\partial t}\frac{\partial(\rho u\varnothing)}{\partial x}\frac{\partial(\rho v\varnothing)}{\partial y}\frac{\partial(\rho u\varnothing)}{\partial z} = \frac{\partial}{\partial x}\left[\Gamma\frac{\partial\varnothing}{\partial x}\right] + \frac{\partial}{\partial y}\left[\Gamma\frac{\partial\varnothing}{\partial y}\right] + \frac{\partial}{\partial z}\left[\Gamma\frac{\partial\varnothing}{\partial z}\right] + S\varnothing \quad (7)$$

Where:
Γ is diffusion coefficient
σ is prandtl no.

Table 1. Model specification and dimension

Parameters	Model 1	Model 2	Model 3	Model 4
Gas Inlet Dia. (mm)	25	15	20	25
AIR Inlet Dia. (mm)	25	15	20	25
Outlet Dia. (mm)	140	140	140	140
Centre pipe Dia. (mm)	25	15	20	25
Burner Dia. (mm)	90	90	90	90
Inlet pipe length (mm)	43	43	43	43
Centre pipe length (mm)	27.5	55	220	110
Max. Temp (k)	2246	2242	2116	2087

Table 2. Details of mesh

Types	Selections
physical reference	CFD
solver preference	fluent
mapped mesh type	Hexahedral
Relevance	100
export format	standard
element order	linear
size function	Curvature
relevance centre	Fine
span angle canter	fine
curvature normal angle	Default (11.2 deg)
min size	Default
maximum face size	2.0mm
growth rate	Default (1.10)
minimum edge length	2.0 mm
Smoothing	Medium
mesh metric	None
inflation option	Smooth transition
transition ratio	0.272
maximum layers	2
Skewness	Min=1.3 and Max=0.9
growth rate	1.2
Nodes	10793
Elements	9943

S is the generalized source term
For continuity, $\varnothing$ = 1, Γ = 0, S = 0
For momentum, $\varnothing$ = {u, v, w}, Γ = f (μ)
For energy, $\varnothing$ = e (or h), Γ = k/cp, S
Using the finite volume method (FVM) ANSYS fluent integrate the generalized species transport equation as follows

$$\int_{\Omega} \frac{\partial}{\partial t}(\Phi)\, d\Omega + \int_{s} \frac{\partial}{\partial x_j}\left(\rho U_j \Phi - \frac{\Gamma\Phi}{\sigma\Phi}\frac{\partial \Phi}{\partial x_j}\right) dS = \int S\Phi d\Omega$$

2.4 Boundary Conditions

Inputs for the model are used as mass flow rate of air and Fuel. Mass Flow rate of both Air and Fuel are taken as 0.05 Kg/m^3 and 0.009 Kg/m^3 respectively. Temperature of Air is 300K and Fuel is 285K. Wall temperature was taken as a constant, 300 K. Turbulence Intensity is taken as 5% at all inlets and Outlet.

2.5 Thermal Physical Properties

The thermal physical properties of LPG, Sic foam, air and steel are discussed in Table 3-6 respectively.

3. Results and Discussion

ANSYS Fluent was used to simulate the mixing and reaction of Fuel and Oxidizer through a two layer

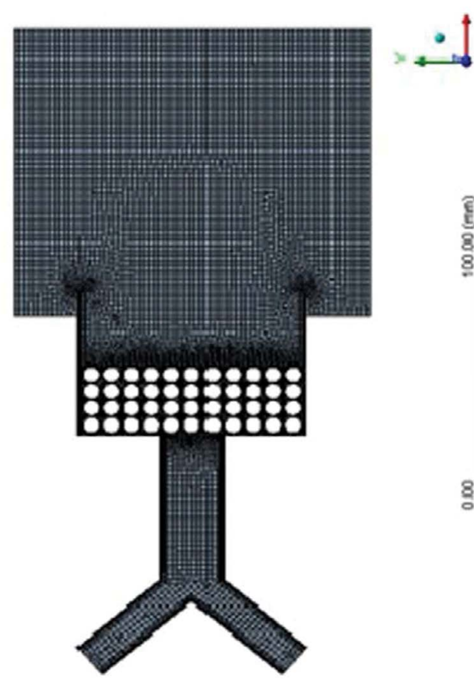

Figure 3. Computational mesh.

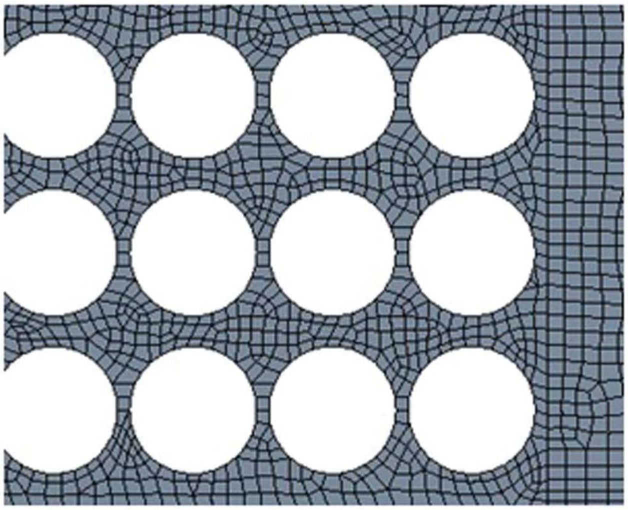

Figure 4. Zoomed hexahedral mesh in pre-heating zone.

Table 3. Thermo - Physical properties of LPG[12]

Boiling Point	-42 °C
Density	1.898 kg/m3 (15°C)
Thermal conductivity	0.010- 0.017w/m°C
Limits of Flammability	2.15% to 9.6% LPG/air
Auto ignition Temperature	470 °C

Table 4. Thermo - Physical properties of dry air[13]

Thermal conductivity	24.35 mW/(m K)
Density	1.276 kg/m^3
Specific heat capacity (Cp)	1.006 kJ/kgK
Dynamic Viscosity	1.1845x10^{-5}Kg/m.s

porous burner of different sizes. The variation in the model was due to different measurement values of centre pipe length and fluid inlet diameter. The centre pipe length was 27.5mm, 55mm, 110mm and 220mm each, whereas the fluid inlet diameter was 15mm, 20mm and 25mm, (Table 1). The burner was evaluated considering turbulence model and Species Model. Total six 3-D models are considered for simulation and results are taken as Contours of Temperature. As we can see from Figure 5, the maximum surface temperature was recorded to be 2046k (model 1) having centre pipe length of 27.5mm and 25 mm inlet pipe diameter. The temperature of model 2 (Figure 6) having 55mm center pipe length and 15mm fluid inlet diameter, was 2242 k which is slightly lower than the temperature of model 1. The maximum surface temperature at the top of the burner for model 3 having 220 mm center pipe length and 20 mm inlet diameter was 2116 k (Figure 7). The maximum temperature for model 4 having a center pipe length of 110 mm and 25 mm fluid inlet diameter was 2087 k (Figure 8). One can see a yellow radish flame generating inside the mixing tube (Figures 7, 8), which might cause flashback or backfire. Flashback is a big issue in a pre-mixed burner and can occur when the gas velocity becomes lower than the flame speed. In this study, it was found that increasing the centre pipe length above 55 mm for the given mass flow rate of air and fuel might raise the chance of flashback. Moreover, as we can see from Figure 9, increasing the pipe length above the range of 27-55 mm not only raise the chance of flashback but also lower thesurface temperature by 250 k. The relationship between the fluid inlet diameter and the surface temperature was almost linear (Figure 10).

Table 5. Thermo - Physical properties of sic foam[14]

Thermal conductivity (1000)	120 to 170 W/m-K
Density	3.0 to 3.2 g/cm3
Thermal expansion	4.0 to 4.5 μm/m-K
Specific heat	670 to 1180 J/kg-K

Table 6. Thermo -Physical properties of copper steel[15,16,17]

Thermal conductivity	56BTU/hr ft °F
Density	0.284 (lbs/in^3)
Specific heat capacity (Cp)	0.12 (Btu/(lbm oF))

4. Conclusion

Based on the computational analysis a maximum temperature of 2246k was observed for porous burner model having centre pipe length of 27.5 mm and 25 mm inlet pipe diameter. It was observed that the reaction and ignition of mixture of fuel and Oxidizer is starting from the pre heating zone. A high temperature Flame is beginning to generate from the steel balls zone which is visible in temperature contours. From the present study the following important conclusions can be made:

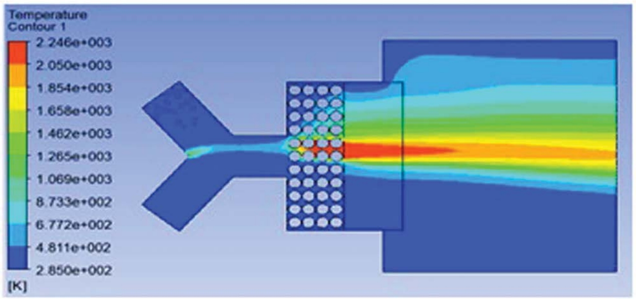

Figure 5. Temperature distribution (Model 1).

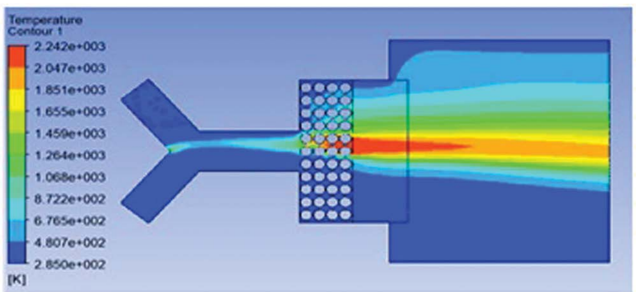

Figure 6. Temperature distribution (Model 2).

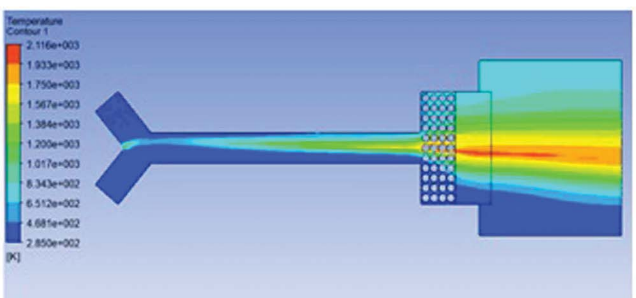

Figure 7. Temperature distribution (Model 3)

- Increasing the centre pipe length by half (27.5mm – 55mm) brings a slight drop of surface temperature of about 4 k.
- From the temperature contours it was observed that increasing the center pipe length above 55mm leads to reduced surface temperature by about 250k.
- Increasing the fluid inlet diameter by 5mm raised the surface temperature by about 300k.
- Based on the insight obtained from the CFD simulation, increasing the center pipe length above the range of 27mm to 55mm, might increase the chance of flashback.

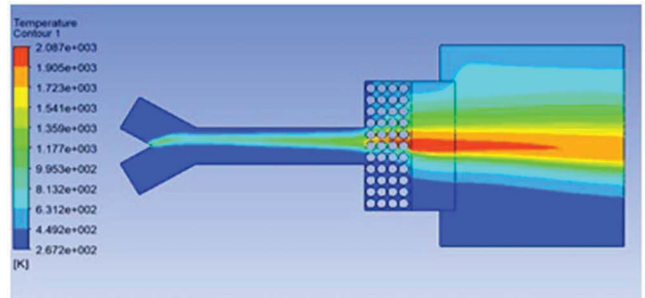

Figure 8. Temperature distribution (model 4).

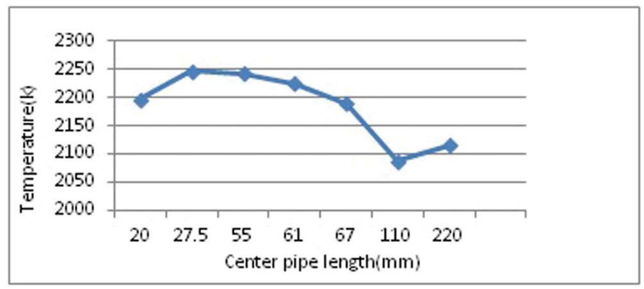

Figure 9. Effect of centre pipe length on the output temperature.

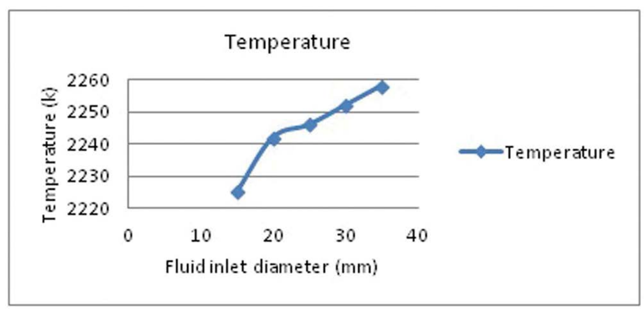

Figure 10. Effect of fluid inlet diameter on the output temperature.

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