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MODELLING AND ANALYSIS OF WATER HEATING USING RECOVERED WASTE HEAT FROM HOT FLUE GASES OF CHULHA

Saravanna J. Y., Rahul Kantamnen, Nizvan Fasil, Seralathan Sivamani, Hariram V., Micha Premkumar T. and Mohan T.
Department of Mechanical Engineering, School of Mechanical Sciences, Hindustan Institute of Technology and Science Padur, Tamil Nadu, India
E-Mail: siva.seralathan@gmail.com

ABSTRACT

The study on heating water for domestic applications by using low grade waste heat recovered from the exhaust flue gas of Chulha is analyzed theoretically as well as experimentally. Two different material combinations are considered for the hot fluid domain (shell) and cold fluid domain (pipe). Theoretical analysis is carried out to estimate the time required to heat the water from its room temperature to 75^{o}C by transfer of heat energy. Numerical investigations are carried out to validate the findings obtained theoretically. Time required in raising the water temperature from its room temperature of 27^{o}C to 75^{o}C is 8 hr for a stainless steel shell - stainless steel pipe combination WHRS. This heating time is reduced by around 4 hr using stainless steel shell - copper pipe combination WHRS. Using biogas as a fuel for the Chulha, the cost of heating the water is reduced to 1.90 Paisa per kg and the cost saved per year on biogas by a typical Indian household is estimated to be 3580 in Indian rupees. Numerical simulation showed a good agreement between the simulation results and theoretical analysis. This WHRS can be used to recover the low grade waste heat released through chimney exhaust flue gas by domestic applications like fireplace, domestic water heating boiler thereby reducing the conventional energy consumption as well as minimizing the environmental degradation.

Keywords: waste heat recovery, flue gas, water, heat transfer, chulha, CFD.

INTRODUCTION

Chulha is a hindi word spoken widely in India which means *cook stove* or *fireplace*. Cook stoves that uses biomass such as dried animal dung cake, agricultural waste, saw dust cake and firewood as a fuel are known as biomass stoves. These biomass stoves cater to the cooking needs of nearly seventy three percent of India's 1.25 billion populations. The fixed Chulha with smoke removal facility is referred to as smokeless Chulha and these are modified versions of the traditional Chulhas. These are designed to save fuel consumption through better combustion by shielding the fire with provision for air supply and removal of exhaust flue gases and smoke through chimney. The thermal efficiency of these Chulhas are high with values around 25% to 35% and also consumes 40% to 60% lesser fuel than traditional Chulhas. These types of Chulhas are promoted actively by MNRES, Government of India under National Biomass Cookstoves Programme, KVIC, OREDA, various State Government agencies as well as by non-governmental organizations in the context of concerns over health, climate change and energy security [1].

Fireplace is also used for heating the room. These are a structure made up of metal, stone or brick. Modern fireplaces have variable heat efficiency based on their superiority of the design. Figure-1 shows the typical Chulha / fireplace used in India.

In a developing country like India, the demand for energy is growing day by day. With growing climatic concerns across the globe along with soaring energy costs, innovative, cost effective and accessible solutions with the aim in reducing energy consumption and improving its efficiency has to be developed. Waste heat recovery system (WHRS) is one such solution to capture the low grade waste heat carried away by the fluids such as gases and fluids from the systems like boiler, fireplace, Chulha, cooking stove, internal combustion engines, etc. Otherwise, these low grade waste heat energy would have been lost to the surroundings without any productive use raising only the environmental concerns [2-7].

Apart from using electrical heaters, in rural India, fossil fuel is the most predominant energy source used for heating the water for domestic purposes. The environmental issues and its drawbacks can be solved by using WHRS for these purposes. It is understood that nearly 65% to 75% of the heat produced by the Chulha is lost up through the chimney. Therefore, innovative waste heat recovery systems are to be evolved in order to recover this waste heat from the flue gases of Chulha being sent to the atmosphere through chimney.

Several studies were carried out theoretically, experimentally as well as numerically on recovering the low grade waste heat from the flue gases involving different industrial / domestic applications. Mahmoud Khaled *et al.* [5] experimentally investigated a WHRS by using the chimney exhaust gas for heating the water in the residential building. The heat input was varied and the gas flow rates through the pipes were noted. The temperatures at different locations of WHRS were measured. The results showed that the water temperature increased by 68^{o}C by one hour. This was due to the radiation and convection heat transfer of flue gases at the bottom side of WHRS which caused high heat transfer rate to the water.

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Figure-1. Typical Chulha with chimney exhaust for flue gas.

Hanning Li *et al.* [8] studied a case on using the low grade waste heat which was available in large quantities from the process industries as a heat source to dry the biomass, pine chip at 60 wt% moisture. These dried materials was used an input fuel for the 40 MW power plant thereby reducing the energy consumption significantly.

Chaojun Wang *et al.* [9] performed a case study on recovery and use of the exhaust flue gas waste heat to pre heat the condensed water by using low pressure economizer in a 600 MW power plant. This method of using waste heat to preheat the water resulted in considerable amount of energy savings (i. e., standard coal equivalent at 2 to 4 g/kWh) besides reducing CO_2 emissions. Petr Stehlik [10, 11] discussed the characteristics of heat exchangers and heat transfer equipments used in waste to energy systems. The author dwelt in detail about these WHRS, its design, arrangement as well as optimization. The author also suggested innovative, instinctive design and refined approach as well as using computational fluid dynamics tools. Optimum design of WHRS from idea to industrial application can be largely contributed by CFD as well as experimental approach.

Xiaojun Shi *et al.* [12] performed both theoretical and experimental investigations on using a finned tube compact heat exchanger as a heat recovery steam generator by recovering the latent heat from the exhaust flue gases. Similar studies on utilizing the low grade waste heat recovered by WHRS were carried out by Bebar *et al.* [13].

Simulations of heat transfer and fluid flow by using computational fluid dynamics (CFD) methodology within the WHRS provides useful information during the design phase. This approach contributes substantially in improving the design [11, 14]. Jiri Hajek [15] applied CFD on a case study involving design optimization of a heat exchanger by using commercial software code ANSYS Fluent. Turbulence was modeled by a well-known k-ε model.

Mukesh Rathore *et al.* [16] numerically studied an internal combustion engine based WHRS using ANSYS Fluent software. Numerical study on recovery of waste heat from a tunnel kiln supplied with electricity was studied by Linsheng Wei *et al.* [17]. 4443 kilograms of coal was saved a year for the inlet water temperature of 285 K.

Numerical studies on the finned type heat exchangers used in the exhaust of internal combustion engines for recovering the exhaust waste heat was studied by Hatami *et al.* [18]. Based on the studies, the authors established that SST k-ω and RNG k-ε turbulence models were the suitable viscous models to obtain results with accordance to experimental data. Similar numerical investigations using CFD as a tool were performed by various researchers [19, 20, 21, 22, 23] using k-ε as the turbulence model as it proved to be stable and robust.

Based on the literature review, it is observed that WHRS plays a prominent role in the recovery of low grade waste heat which could be used effectively in reducing the energy consumption rate as well as reducing the environmental pollution hazards besides increasing the overall thermal efficiency of the system. In this present study, a storage type heat exchanger is used as the WHRS. The hot flue gases passes through the pipes and the water to be heated is stored in the storage type shell arrangement.

The objective of the present study is to analyze the storage type heat exchanger used to heat the water by utilizing the low-grade waste heat from chimney exhaust flue gas of a Chulha. Two different materials are chosen for the pipe through which the hot flue gas passes through. The study is carried out in two stages. Initially, theoretical analysis is carried out which is verified and validated numerically. Subsequently, the numerical studies are carried out by varying the materials used for the pipes of the storage type heat exchanger.

THEORETICAL ANALYSIS

Table-1 shows the dimensional details of the WHRS. Table 2 shows the properties of the flue gas and water at 200°C and 27°C respectively. By heat balance concept [24], the rate of heat transferred by the flue gas is equal to the rate of heat absorbed by the water, thereby

$Q_{\text{flue gas}} = Q_{\text{water}}$

$$\mathrm{m}\dot{m}_f C_{pf}\left(T_{f1} - T_{f2}\right) = \mathrm{m}\dot{m}_w C_{pw}\left(T_{w1} - T_{w2}\right) \quad (1)$$

ARPN Journal of Engineering and Applied Sciences

Table-1. Dimensional details of the WHRS.

Outer diameter of the stainless steel [AISI 304] shell (D_s)	0.38 m
Thickness of the shell	0.001 m
Length of the shell (l_s)	1.0 m
Diameter of the copper pipes (D_c)	0.042 m
Thickness of the copper pipes	0.001 m
Length of the copper pipes (l_c)	1.40 m
Surface area of the copper pipe, $A = 2\pi r_c l_c$	0.132 m^2
Cross sectional area = πr_c^2	0.542×10^{-3} m^2

Table-2. Properties of the flue gas and water.

Flue gas at 200°C		**Water at 27°C**	
Velocity (v_f)	9 m/s	Inlet temperature (t_w)	27°C
Inlet temperature (T_{f1})	200°C	Density at 27°C (ρ_w)	998.025 kg/m^3
Density at 200°C (ρ_f)	0.748 kg/m³	Specific heat (C_{pw})	4178 J/kgK
Kinematic viscosity (γ_f)	32.80×10^{-6} m^2/s	Convective heat transfer coefficient (h_w)	1000 W/m^{2o}C
Thermal conductivity (K_f)	0.04012 W/mK		
Specific heat (C_{pf})	1097 J/kgK		

The mass of water (m_w) is obtained using its density and volume and it is expressed by the equation, m_w = Density of water (ρ_w) × Volume of water (V_w).

Volume of water (V_w) held in the WHRS is expressed as $V_w = \pi r_s^2 l - 9\left(\pi r_c^2 l\right)$ and it is found to be 0.101 m^2. The mass of water (m_w) is estimated to be 100.766 kg. Based on this, the mass flow rate of the flue gas (m_f) at velocity (v_f) 9 m/s is expressed as

$$m_f = v_f \times Cross\ Sectional\ Area \times \rho_f \quad (2)$$

The convective heat transfer coefficient (h_f) is found by using the Nusselt number (Nu) for staggered cylindrical pipes arrangements.

$$\text{Nu} = CRe^n \quad (3)$$

where Re is Reynolds number of the flue gas and it is expressed as

$$\text{Re} = {(v_f D_c)}/{\gamma_f} \quad (4)$$

Based on this, the Reynolds number (Re) is found to be 11524.390.

The values of 'C' and 'n' in equation (2) is given by

${S_l}/{D_c}$= 3 and ${S_t}/{D_c}$ = 3.

The values of 'C' is 0.2860 and 'n' is 0.608 respectively.

Using the values of 'C' and 'n' in equation (2), the Nusselt Number (Nu) is estimated to be 84.30.

Convective heat transfer coefficient (h_f) is also expressed by

$$\text{Nu} = {(h_f \times D_c)}/{K_f} \quad (5)$$

Based on the Nusselt number, the convective heat transfer coefficient (h_f) is found to be 80.526 W/m^2K

The outlet temperature of the flue gas (T_{f2}) is determined using effectiveness and number of transfer unit (NTU) method.

$$\varepsilon = (T_{f1} - T_{f2})/(T_{f1} - T_{w1}) \quad (6)$$

$$\text{N} = AU_o/C_{min} \quad (7)$$

where U_o is the overall heat transfer coefficient and it is expressed as

$$\frac{1}{U_o} = \left(\frac{1}{h_f}\right) + \left(\frac{r_{co}}{K_c}\right) ln\left(\frac{r_{co}}{r_{ci}}\right) + \left(\frac{r_{co}}{r_{ci}}\right)\left(\frac{1}{h_w}\right) \quad (8)$$

and it is found to be 74.382 W/m^2K

$C_{min} = m_f C_{pf}$
$C_{max} = m_w C_{pw}$

ARPN Journal of Engineering and Applied Sciences

Based on the values of U_o, A and C_{min}, number of transfer units (N) is found to be 0.0266.

Effectiveness (ε) based on the number of transfer units is given as

$$\varepsilon = 2\left[1 + C + X[1 + Y/1 - Y]\right]^{-1} \quad (9)$$

where X = $(1 + C^2)^{0.5}$,

$$Y = exp\left(-N(X)\right) \text{ and } C = C_{min}/C_{max} . \quad (10)$$

The values of C, X and Y is found to be 0.0524, 1.001 and 0.9736 respectively. Based on this, the effectiveness (ε) is estimated to be 0.02627.

By equating equations (5) and (8), the flue gas temperature at exit (T_{f2}) is estimated as 195.454°C

The heat transfer rate of flue gas (Q_f) is expressed as

$$Q_f = m\dot{m}_f Cp_f\left(T_{f1} - T_{f2}\right) \quad (11)$$

and it is found to be 1674.603 W

Based on the theoretical study, the outlet temperatures of flue gas as well as water are estimated with respect to time and the details are shown in Table-3 and 4 respectively. It is found theoretically that the temperature of flue gas (i.e., hot fluid) at outlet under steady state condition as 196.58°C after four hours. The outlet temperature of flue gas varied from 118°C to 196°C. As the copper pipes carrying hot flue gas attained steady state condition, subsequently there is a minor change in the flue gas outlet temperature. It took only four hours for the water to reach the required temperature of around 80°C.

Table-3. Flue gas temperature at outlet with respect to time.

Time 't' (min)	**Flue gas outlet temperature 'T_{f2}'** (°C)
After 10 minutes	118.086
After 20 minutes	159.043
After 30 minutes	172.695
After 40 minutes	179.521
After 50 minutes	183.617
After 60 minutes	186.347
After 120 minutes	193.173
After 180 minutes	195.449
After 240 minutes	196.586

Table-4. Temperature of water at outlet with respect to time.

Time 't' (hr)	**Water outlet temperature 'T_{w2}'** (°C)
at 1.0 hour	41.032
at 1.5 hour	48.479
at 2.0 hour	55.640
at 2.5 hour	62.799
at 3.0 hour	69.859
at 4.0 hour	84.278

NUMERICAL ANALYSIS

Three dimensional models required for the numerical analysis are developed using the modeling software, CATIA V5 R20. Dimensional details of the WHRS computational domain are shown in Table 1. As the computational domain involves flow of two different fluids, the cold water shell domain and the hot flue gas pipe domain are modeled and meshed separately. Part modeling and assembly modules techniques are used to design this WHRS. Figure-2(a) shows the cold fluid domain (i.e. shell) in which the water to be stored is stored in this present study. The pipes through which the hot flue gases passes through are designed with respect to the inner and outer diameter of the shell as seen in Figure-2(b). Figure-2(c) shows the assembled view of the present storage type heat exchanger.

The numerical analyses are performed using ANSYS FLUENT V15. The numerical analysis is carried out with two different material combinations. In the first type, both the pipes and shell is considered to be made up of stainless steel material (AISI 304) whereas in the second type, the shell alone is considered to be of stainless steel (AISI 304) and the pipes, through which the hot flue gases flow through is assumed to be copper material. These two computational domains are analyzed separately. The results obtained from these numerical studies are compared to identify the effective combination of materials used in this heat exchanger.

Figure-2(a). Cold fluid domain - Shell (b) Hot fluid domain - Pipes **(c)** Assembled storage type water heater.

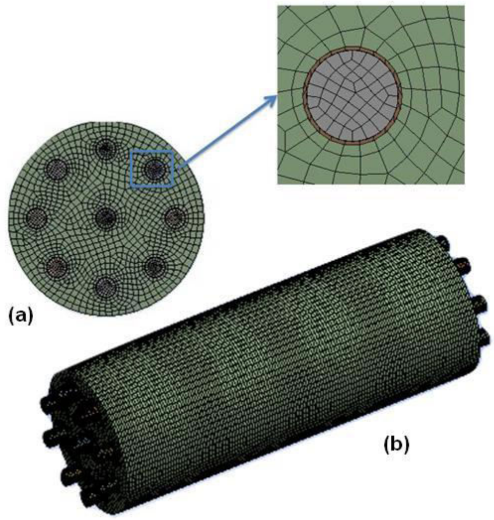

Figure-3(a). Structured mesh with closer view of the mesh nearer to the wall regions (b) Meshed computational domain.

3D model of the computational domain in IGS format is imported to the ANSYS Fluent module. Meshing is carried out using ANSYS meshing module. Coarse mesh is used in the fluid domain in general and fine meshing is provided at the interfaces, walls and near the edges. The aspect ratio is set at 1.20. Topology checking is kept on during the meshing. Figure-3 shows the structured mesh generated in the computational domain. The closer view of the mesh near the wall regions are shown in Figure-3(a). The number of nodes and elements generated in the pipes domain are 69347 and 39339 respectively. Similarly, the number of nodes and elements in the shell domain are 290757 and 253848 respectively. The total number of nodes and elements generated in the whole fluid domain are 360104 and 293187 respectively.

Hot flue gas enters through the pipe at 200˚C and the water to be heated is stored in the shell domain at 27˚C. Coupled wall interface is introduced between the hot flue gas pipe domain and cold water shell domain as they are modeled and meshed separately. Under the given temperature and pressure conditions, the speed of the sound is much greater than the real fluid flow velocity and thereby, the fluid model is incompressible. For the hot fluid domain i.e., pipes, the boundary condition at the inlet is mass flow rate and the outlet boundary condition is static pressure. For the cold fluid domain i.e., shell, the boundary condition at the inlet is mass flow rate and the boundary condition at outlet is static pressure. The equations of mass, momentum and energy are solved to model the fluid flow and heat transfer within the computational fluid domain.

The continuity equation is $\frac{\partial \rho}{\partial t} + \nabla.\left(\rho U\right) = 0$ (12)

The momentum equation is

$$\frac{\partial\left(\rho U\right)}{\partial t} + \nabla\left(\rho UU\right) = -\nabla p + \nabla\tau + S_M \quad (13)$$

The energy equation is

$$\frac{\partial\left(\rho h_{tot}\right)}{\partial t} - \frac{\partial p}{\partial t} + \nabla\left(\rho U h_{tot}\right) = \nabla\left(\lambda\nabla T\right) + \nabla\left(U\tau\right) + US_M + S_E \quad (14)$$

Roughness on the walls is neglected and no-slip conditions are assumed on all the walls. Scalable wall functions are invoked for the near wall treatment. Realizable k-ε turbulence model is used to achieve the closure for all the governing equations under transient conditions. The time step for all stainless steel domains is 3600 seconds with eight number of time steps. Similarly, for stainless steel-copper domain, the time step is 3600 seconds with four number of time steps. Convergence criteria for all the residuals are set to 1 x 10^{-5}.

Contours of temperature, pressure and velocity are taken at different axial locations along the flow direction of the flue gas in the heat exchanger with reference to the mid axial plane at location ‘c’ as seen in Figure-4.

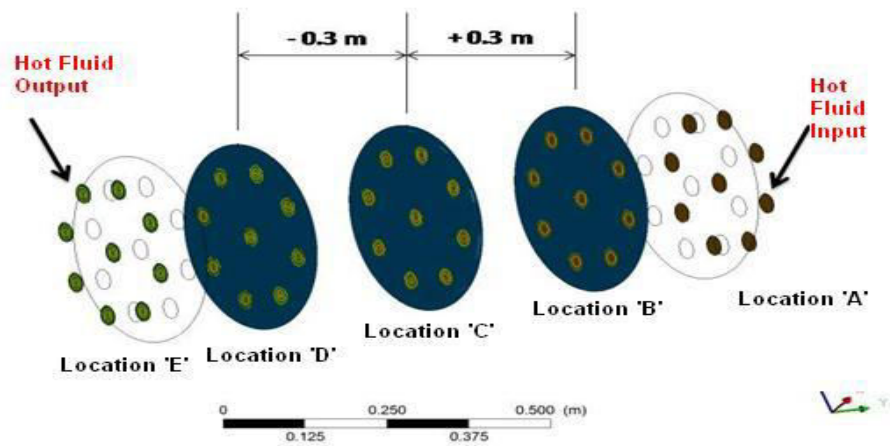

Figure-4. Locations of axial plane along the computational domain.

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Stainless steel shell - Stainless steel pipe domain. The temperature distribution contours at various axial planes along the hot fluid flow direction from inlet to outlet is shown in Figure-5.

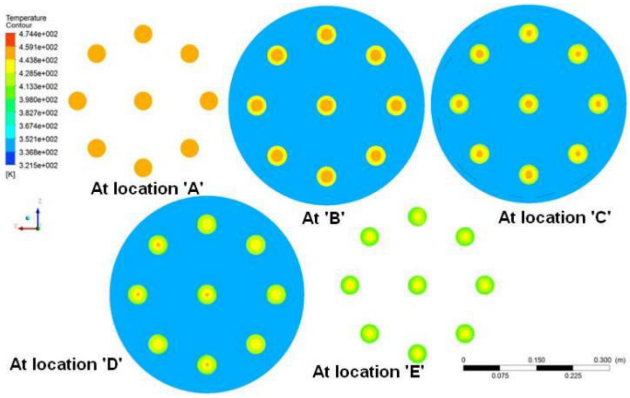

Figure-5. Temperature distribution contours at various axial planes along the hot fluid flow direction.

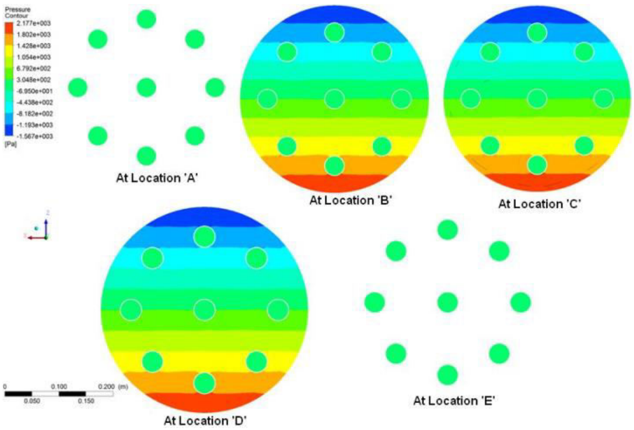

Figure-6. Pressure distribution contours at various axial locations along the hot fluid flow direction.

On observing the temperature contours at different axial locations, it is clearly seen that the flue gas temperature decreases from 459 K to 410K by losing its heat energy. Heat transfer takes place between the flue gas and water through the walls of the pipes along the flow direction as seen in Figure-5. The contour clearly shows a uniform distribution of water temperature within the shell at around 340 K which is raised from the initial temperature of 300 K. The time required in raising the water temperature from its initial temperature of 27°C to 75°C is eight hours.

The contours of pressure distribution at various planes along the hot fluid flow direction from inlet to outlet are shown in Figure-6. The flue gas flows from the inlet to the outlet of pipe domain without any adverse pressure drop along the flow direction.

Velocity distribution contours at various axial planes along the hot fluid flow direction from inlet to outlet are shown in Figure-7. The velocity of the flue gas at entry of the pipe domain is at around 9 m/s. This flue gas velocity decreases slightly to around 8.50 m/s along the flue gas flow direction which favors the flow to occur without any blockage and adverse pressure drop. As this heat exchanger is a storage type, the water within the shell domain is stagnant. Therefore, the velocity of the water is zero as seen in Figure-7.

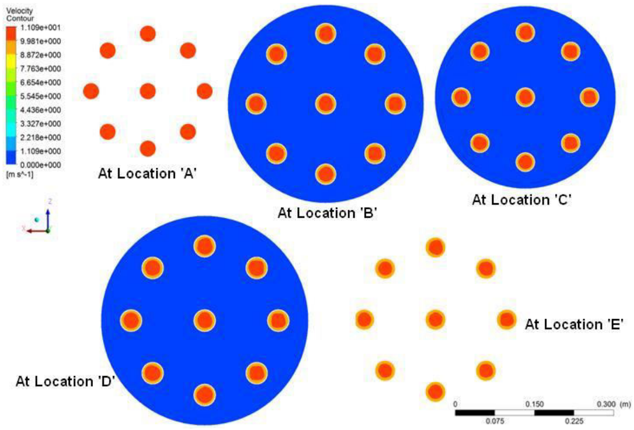

Figure-7. Velocity distribution contours at various axial locations along the hot fluid flow direction.

Stainless steel shell - Copper pipe domain. The temperature distribution at mid axial plane (location 'C') of the computational domain is shown in Fig. 8. The contour clearly shows a uniform distribution of water temperature within the shell at around 360 K which is raised from its initial temperature of 300 K. This raise in temperature is attained by four hours.

The contours of pressure and velocity distribution at mid plane of the domain along the hot flue gas flow direction are shown in Figures 9 and 10 respectively. As the water in the shell domain is stagnant, the velocity of the water is zero. Also, no blockage as well as adverse pressure drop is observed along the flue gas flow direction. The observed numerical results are in close agreement with the theoretical data.

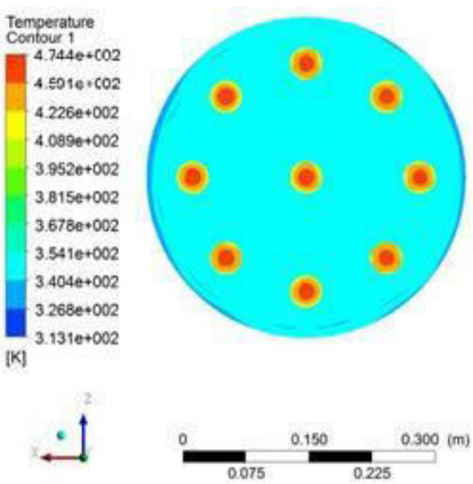

Figure-8. Temperature contour at mid plane of the domain.

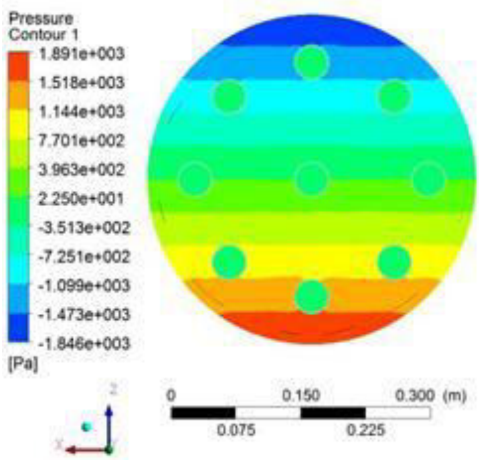

Figure-9. Pressure contour at mid plane of the domain.

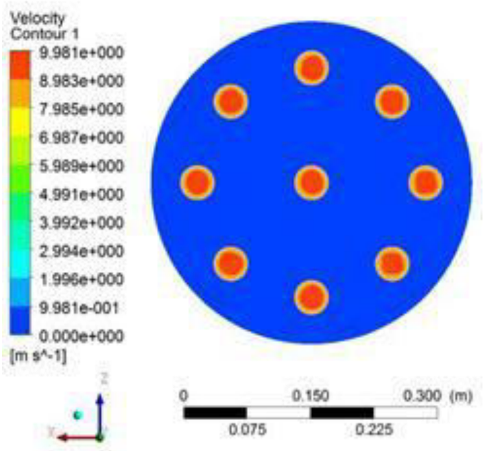

Figure-10. Velocity contour at mid plane of the domain.

Further, economic analysis is also carried out to estimate the cost saved on the expense of fuel in raising the water temperature after implementing the WHRS. In rural households of India, biogas is used as the fuel for cooking purposes and it is the predominantly used fuel for Chulha. Therefore, by using biogas as a fuel for the Chulha, the cost of heating the water up to 70°C without WHRS is 3 Paisa per kg whereas, the same cost by using the WHRS is 1.90 Paisa per kg. The cost saved per year by a typical Indian rural household is estimated to be around Rs.3580 (in Indian rupees). The total cost incurred for this WHRS for Chulha to heat the water is Rs.3000 (in Indian rupees). The payback period is estimated to be 10 months.

CONCLUSIONS

A WHRS is used to recover the low grade waste heat from the Chulha exhaust flue gases and heat the water for domestic purposes. Based on the theoretical and numerical analysis, the following conclusions are made:

- Time required in raising the water temperature from its initial temperature of 27°C to 75°C is 8 hr for a stainless steel shell - stainless steel pipe combination WHRS. This heating time is reduced to around four hour by using the stainless steel shell - copper pipe combination WHRS.
- Hot fluid domain (i.e. shell) made up of stainless steel material and cold fluid domain (i.e. pipes) made with copper material is observed to provide the effective thermal combination.
- Theoretical values are verified with the data obtained by CFD simulation and there is a good agreement between them.
- Substantial energy cost is saved by recovering the low grade waste heat from exhaust flue gas. The cost saved per year by a typical Indian rural household using biogas as a fuel is estimated to be around three thousand six hundred in Indian rupees.

Payback period is estimated to be 305 days after installing this WHRS in the existing Chulha exhaust chimney.

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