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Analysis of Flow Dynamics of Carbon Monoxide Emitted from Cook Stoves in Closed Room Using CFD

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Abstract:
Wood being one of the major sources for cooking in developing countries has also been key for indoor air pollutions. Many studies and improvements on the stove have been conducted to enhance combustion efficiency and minimize emission. Although many Improved Cooking Stoves (ICS) programs has been widespread, due to design limitation together with operational and fuel factors have hindered the targeted emission reduction. Several studies in developing countries have shown that the even ICS have not been able to reduce the adverse impact on human health due to the use of solid biomass fuel. Despites the limitation in stove performance, alternatives have to be used to reduce the indoor air pollution till better cooking and heating system is in place in the developing countries. Proper ventilation and stove placement might be one of the few solutions. To provide an effective passive ventilation scheme, flow dynamics of the pollutants from stove to indoor space and outdoor needs to be predicted. This paper discusses about the application of Computational Fluid Dynamics (CFD) tool to predict the pollution flow pattern and dispersion dynamics with different ventilation placement and stove location. The study also considers potential thermal energy conservation in the living space with optimum ventilation.

Keywords: Indoor Air Pollution, Emission, Ventilation, Flow Dynamics

1 Introduction

The aim of this paper is to focus on the flow dynamics of carbon monoxide in close room without any inlet or outlet. The flow dynamics of the carbon monoxide can be used to purpose the solution of the natural ventilation scheme to the people of the developing nation.

Many people in developing nations like Nepal still rely on biomass for cooking and heating purpose. Burning biomass produces different pollutants like carbon monoxide which when inhale and mixed with hemoglobin would produce carboxy-hemoglobin. This carboxy-hemoglobin is injurious to health and acts as poison in the body. Thus, in long term, this has negative impact on the health of the people causing other pulmonary diseases like chronic obstructive pulmonary disease.

In-order to minimize this, many programs has been launched from different governmental and non-governmental agencies but desired milestone has not been reached yet. This is due to three major factors involved while designing and using stoves. Those factors are design factor, operational factor and fuel factor. Operational and fuel factors are user dependent factors whereas design depends on the designer.

In the design factor, there is the compromise between combustion and heat transfer efficiency which are inversely dependent with each other. Thus, enhancing combustion efficiency will decrease the amount of pollutants in one hand whereas in other hand it reduces the heat transfer efficiency which results for the increase of time of cooking. All the operations and fuel factors used while designing stove has its own fixed fuel size and standard operational parameters which cannot be achieved while used by the user while cooking or heating.

Despites the limitation, alternatives have to be used to reduce the indoor air pollution until better cooking system is in place in the developing countries. Proper ventilation and stove placement might be one of the few solutions. To provide an effective passive ventilation scheme, flow dynamics of the pollutants (like CO) from stove to indoor space and outdoor needs to be predicted.

1.1 Numerical Model

Numerical simulations used in this study follows the law of conservation of mass, energy and momentum. Mass conservation equation can be written as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

Similarly, momentum equation representing x, y and z directions can be written as:

$$\frac{\partial(\rho V)}{\partial x} + \nabla.(\rho V \mu) = \nabla.(\mu \nabla \mathrm{V}) - \frac{\partial P}{\partial x} - \frac{\partial P}{\partial y} - \frac{\partial P}{\partial z} + B + F \quad (2)$$

Energy can also be written as:

$$\nabla.(\rho h \mu) = \nabla.(k \nabla \mathrm{T}) + S \quad (3)$$

Where, S in volumetric rate of heat generation, P is pressure, B is body force and F is viscous force

2 Methodology

CFD simulation is done using Ansys Fluent in which the flow analysis of the carbon monoxide coming from the stove is done. Few experiments have been done to analyze the flow velocity of the stove just coming out of the stove. Average velocity is taken as the base of the analysis.

Besides, gas analyzer (Kane 455) is used to find the percentage of carbon monoxide coming out the stove. Experiment to find the velocity of the exhaust gas and percentage of carbon monoxide is done in Energy and Gasification Laboratory, Kathmandu University.

Some mathematical calculations were also done to find out the velocity of carbon mono oxide and combustion efficiency. Combustion efficiency of the stove can be calculated by using the following formula:

$$Combustion\ efficiency = \frac{\%\, CO_2}{\%CO + \%\, CO_2} \quad (4)$$

Since the gas analyzer can display the percentage of both carbon monoxide and the carbon dioxide, combustion efficiency of the stove can be calculated. This is important since the fractional mass of carbon monoxide is needed to find the overall concentration in the room after certain time.

Similarly, the velocity of the carbon monoxide can be calculated by using the formula listed below:

$$V_{CO} = {}^{7}/_{3} * C * combustion\ efficiency \quad (5)$$

Where, C is carbon contain in the wood or fuel

Some experiments were done to find out few parameters for the simulations. The experimental results are mentioned below:

V_{co}	0.7 m/s
Percentage of CO	10
Percentage of CO_2	89

Also, using the mathematical formula to calculate the velocity of the CO, we can obtain the velocity of CO to be 0.68.

The experimental results and the mathematical results are close for velocity after combustion.

Similarly, the combustion efficiency of the stove is calculated by using the relation mentioned in methodology section and is found to be 90 % on approximation.

The values obtained from the experiments and calculation is used as input parameters for the Ansys.

3 Result

3.1 Closed Room (with window and door closed)

3.1.1 Flow pattern of carbon monoxide

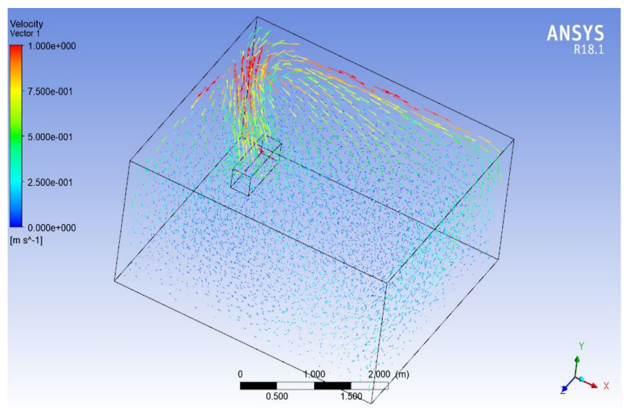

Figure 1: Flow pattern of CO in room from stove

Due to the buoyancy and initial upward velocity gained due to combustion, the CO coming from the stove rises upside with other exhaust gases in absence of any other obstacle. When it reaches to the surface of the ceiling, it moves in the path of lower impedance. During this time some of the molecules of the CO gets diffused due to lower inter molecular bonding. Top portions of walls with corresponding sides with the stoves will have the more concentration of the pollutants initially and it slowly occupies the room volume.

3.1.2 Mass fraction of CO:

From the figure we can see that the mass fraction of the CO is higher in the corresponding walls and top of the room which is justified by the flow pattern of the CO. There is slight increase of the concentration in other portion of the room which is due to diffusion. The flow region of the carbon monoxide will be more polluted region of the room.

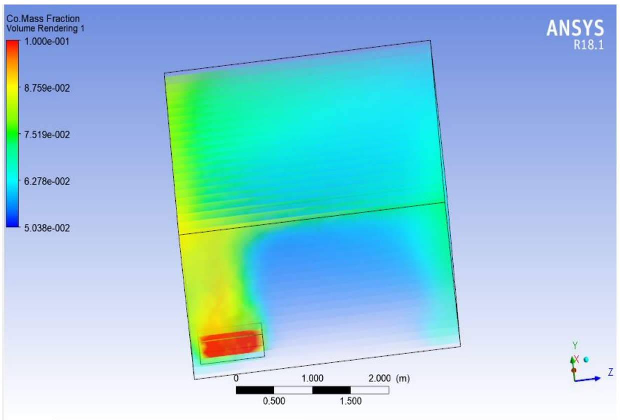

Figure 2: Volume Rendering of CO mass fraction

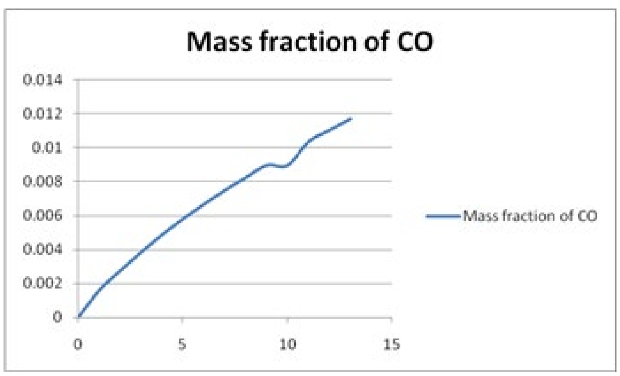

Figure 3: Mass fraction of CO with respect to time

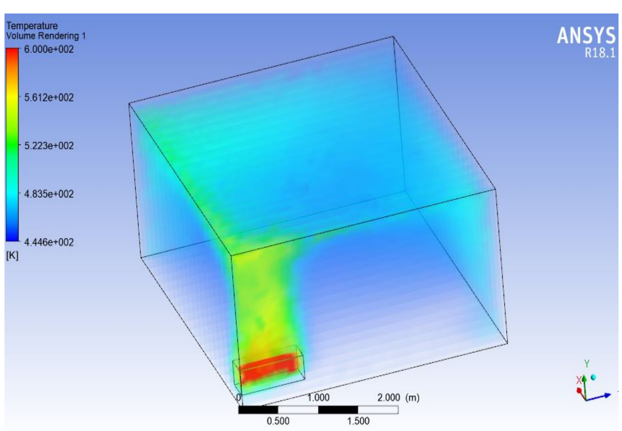

Figure 4: Volume Rendering of Temperature

Figure 3 shows the pattern of increase of the mass fraction in the room with respect to time. It shows that in absence of outlet, CO concentration increases in the room. The graph also shows that mass fraction vs. time graph is somewhat linear nature and can be treated as linear graph.

3.1.3 Temperature profile

Change in temperature or rise in temperature also follows the same pattern as that of the flow of the pollutants. The hot flue gases coming out of the stove after combustions acquired certain heat and rise in temperatures. Temperature of the room is higher at the high concentrated area. The figure also explains that the same this.

3.2 Interpretation of the Result

Stokes number is very important parameter in the fluid flow and is given by:

$$S_{th} = \frac{\varsigma_v}{\varsigma_f} \tag{6}$$

Where, ς_v is the characteristics flow of the fluid in the flow field (carbon monoxide in this case) and, ς_f is the characteristic time of flow fields.

In this case ς_f is zero and the value of the stoke number is infinite or undefined. In the closed room there is no impact of the external factor i.e. the internal state initially is zero. Stoke number greater than one signifies the flow of the carbon monoxide will be the dominant and follow its own pattern. In all the results we can see the flow domination is done by the flow of the flue gases coming out of the stove.

Carbon monoxide has its own flow dynamics in this case and rises up initially while coming out of the stove. In the absence of the obstacle the flow would rise up followed by the diffusion.

3.3 Conclusion

From the result it is clear that the exhaust system or exhaust hood would be effective when placed just above the main combustion zone of the stove. This would lead to minimize indoor air pollution unless affected by any other external sources. Buoyancy is the main factor that carries maximum amount of pollutants to rise.

Besides, there would be certain amount of the pollutants remaining in the room since some of them are diffused due to weak bonding between the molecules. The diffused molecules are quite low in comparison. Thus, the better solution to minimize the effect on the human health is to construct the exhaust system just above the cooking region.

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