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Numerical Study of Fluid Flow and Heat Transfer in a Gas Tank Water Heater System

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Abstract: In this article influence of a vent hood at the exit of exhaust flue gas and flue baffles in the fire tube on the temperature and flow fields of a gas tank water heater system as well as the structure and amount of heat transferred to the water tank has been studied numerically. To do it, the basic equations of fluid flow and heat transfer such as conversation of mass, momentum and energy equations have been solved using finite element method. It has been observed that using a vent hood prevents the gas backflow in the flue and placing the flue baffles increases the heat delivered to the water.

Key words: Fluid flow · Heat transfer · Tank water heater · Computer simulation

INTRODUCTION

Among the energy components, heating systems which use mainly fossil fuel, are particular important. Rising trend of gas consumption in different parts of gas reserves on the one hand and ends of gas reserves on the other hand, is sensible more than before and consequently the efficiency of gas consumption in all consumers is a crucial factor [1]. One of these systems is gas tank water heater that produces domestic hot water at home. A gas tank water heater consists of a burner that heats the water, an inner steel tank that holds the water being heated, fire tube (or chimney) that is located in the middle of system, baffle plates which usually made of metal that sit inside the fire tube, thermal insulation that surrounds the tank to decrease the amount of heat lost to the surrounding, dip tube to allow cold water to enter the tank, pipe to allow hot water to leave the tank, thermostat that reads and controls the temperature of the water inside the tank and a vent hood that lies at the exit of the combustion products. In this paper, influence of the flue baffles placed in the fire tube and a vent hood at the exit of the combustion products on the temperature field, fluid flow and heat transfer structure of a gas tank water heater is studied numerically.

MATERIALS AND METHODS

The simplifications and assumptions of a considered gas tank water heating system for the calculatons are: (1) The system is cylindrical symmetry. So, all temperatute and flow fields discussed in this article are limited in two dimensions. (2) Both water and gas flows are ideal, incompressible and Newtonian. (3) Flows are layered, smooth and stable. Due to density changes for heating process, the Boussinesq approximation is used in the equations of momentum conservation. The momentum and energy equations are linked and must be solved simultaneously [2,3]. For a complete solution of the equations, the continuity equation should be considered. Thus, the basic equations in direction of r and z are:

$$\rho(v_r \frac{\partial v_r}{\partial r} + v_z \frac{\partial v_r}{\partial z}) = -\rho \frac{\partial p}{\partial r} + \mu[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial v_r}{\partial r}) + \frac{\partial^2 v_r}{\partial z^2} - \frac{v_r}{r^2}] \quad (1)$$

$$\rho(v_r \frac{\partial v_z}{\partial r} + v_z \frac{\partial v_z}{\partial z}) = -\rho \frac{\partial p}{\partial z} + \mu[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial v_z}{\partial r}) + \frac{\partial^2 v_z}{\partial z^2}] + \rho g \beta (T - T_0) \quad (2)$$

$$\frac{1}{r}\frac{\partial}{\partial r}(r v_r) + \frac{\partial v_z}{\partial z} = 0 \quad (3)$$

$$\alpha[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T}{\partial r}) + \frac{\partial^2 T}{\partial z^2}] = v_r \frac{\partial T}{\partial r} + v_z \frac{\partial T}{\partial z} \quad (4)$$

where μ is viscosity coefficient of fluid and $\alpha = \frac{k}{\rho c}$ is called diffusivity coefficient of the matter. In order to convert two Navier-Stocks and continuity equations to one equation, we help from the stream function:

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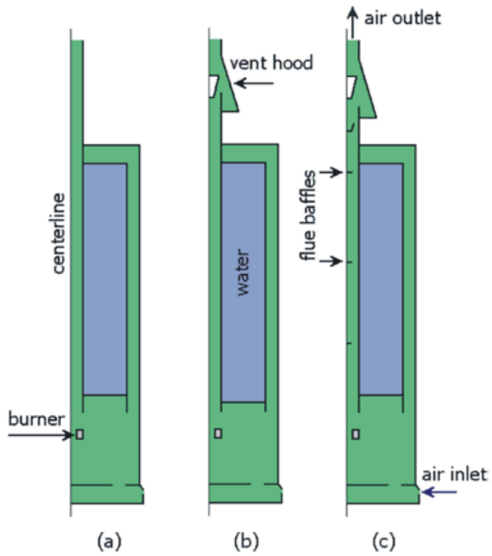


Fig. 1: Sketch of three gas tank water heating systems considered for our computation, (a) without venthood and flue baffles, (b) with vent hood and without flue baffles and (c) with both vent hood and flue baffles

$$v_z = -\frac{1}{r}\frac{\partial \psi}{\partial r} \text{ and } v_r = \frac{1}{r}\frac{\partial \psi}{\partial z} \qquad (5)$$

In parts that circulating flow is considered, the following equation of vorticity is applied [4]:

$$\omega = \frac{1}{r}\left(\frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{\partial^2 \psi}{\partial z^2}\right. \qquad (6)$$

At the rigid surfaces of the viscous fluids non-slip condition has been used. Also the inlet air temperature in the combustion chamber is assumed to be 27°C.

We have considered three cases of a gas tank water heating system for our computation, Figure 1. They are:

case a - without venthood and flue baffles,
case b - with vent hood and without flue baffles and
case c – with both vent hood and flue baffles. In order to enhance the heat exchange between the exhaust flue gas and the water within the tank, baffles have been secured in the exhaust flue. A chain of discs are suspended within the flue to retard the rising gases so that the side wall of the flue absorbs heat and exchanges it with the liquid disposed thereabout.

Calculation of the governing equations with boundary conditions has been made by a 2D finite element method (FlexPDE package [5]). In order to select a suitable computational grid which can leads to numerical errors minimizing, different grids have been studied with different structure and node numbers for this problem. For a better performance of the software, an optimal mesh structure with a fine grid in regions with high field gradients such as flue baffles, vent hood, walls and burner has been selected which could optimize the required memory and computation time with sufficient accuracy.

RESULTS AND DISCUSSION

In Figure 2, Temperature distribution of the system is shown for three considered cases. Heat transfer takes place through the system in three mechanisms of conduction, convection and radiation. A part of the energy of combustion products raises the temperature of the fire tube and tank walls and thus the energy is transferred to the water within the tank via conduction. In all cases, cold air inserts into the combustion chamber via intake window (open hole to atmosphere) positioned at the lowest chamber and makes this area to be the coldest part of the system. When there is a vent hood, exit of the combustion products to the out of the system is increasing and so less heat is transferred to the tank wall compared to *case a*. This causes the increasing of temperature difference between the fire tube and the tank water which has been shown by decreasing the temperature of the water tank in Figure 2(b). In *case c*, placing the flue baffles in the fire tube delays heat transfer out of the system. Therefore the heat is diverted to the water tank more effectively than other two cases which is displaced clearly by inreasing the temperture of the water tank in Figure 2(c). It can be seen that the minimum temperature of water is located at the lower left corner of the tank and the maximum at the upper corner of fire tube which is about the boiling point of water.

Figures 3-5 show the velocity vectors of gas and water in three cases studied here. Gas particles have an upward high speed in the vicinity of centerline in the fire tube. The hot gases from the burner chamber are cooled as they rise up the flue or chimney which is in contact with the water being heated, i.e., the hot gas particles velocity as well as their temperature decreases due to heat transport to the water tank. Thus their energy reduces during their upward motion. Since the left wall of the water tank close to the flame has a higher temperature, density of the water particles decreases and moves upward. The momentum exchange between particles will replace cold water particles with higher density. For this reason,

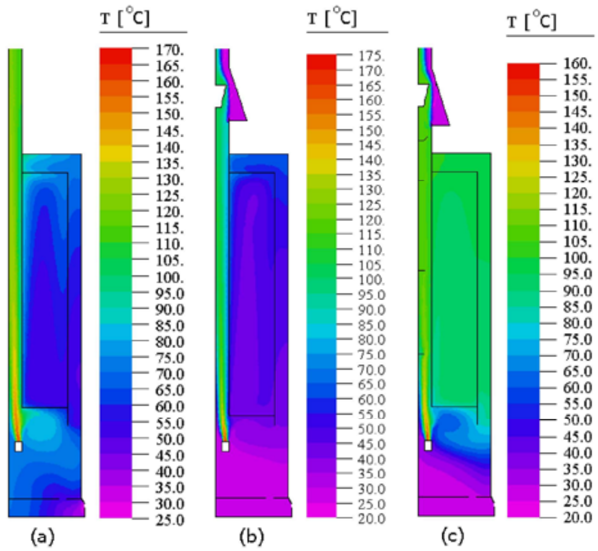
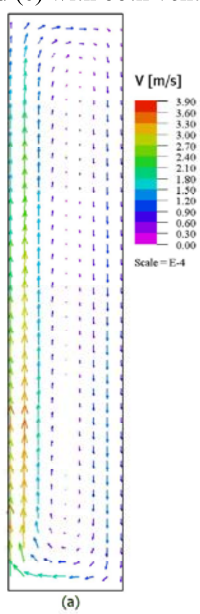


Fig. 2: Temperature distribution of the system in three considered cases (a) without vent hood and flue baffles, (b) with vent hood and without flue baffles and (c) with both vent hood and flue baffles



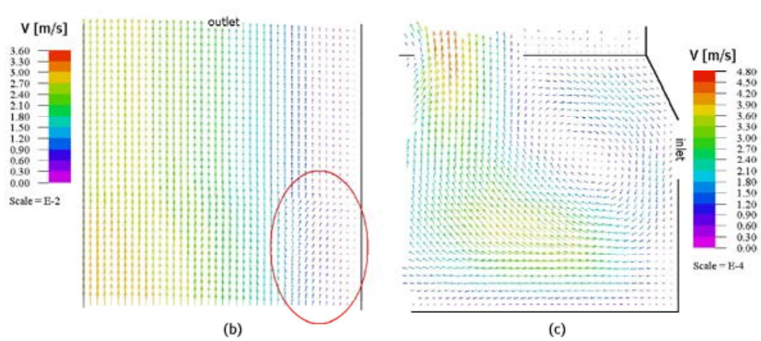


Fig. 3: Distribution of velocity vectors of water and gas in *case a* - without vent hood and flue baffles (a) water tank (b) fired tube and (c) lower space with intake window. The return flow of cold air with high density is more clear in Figure (4-b)

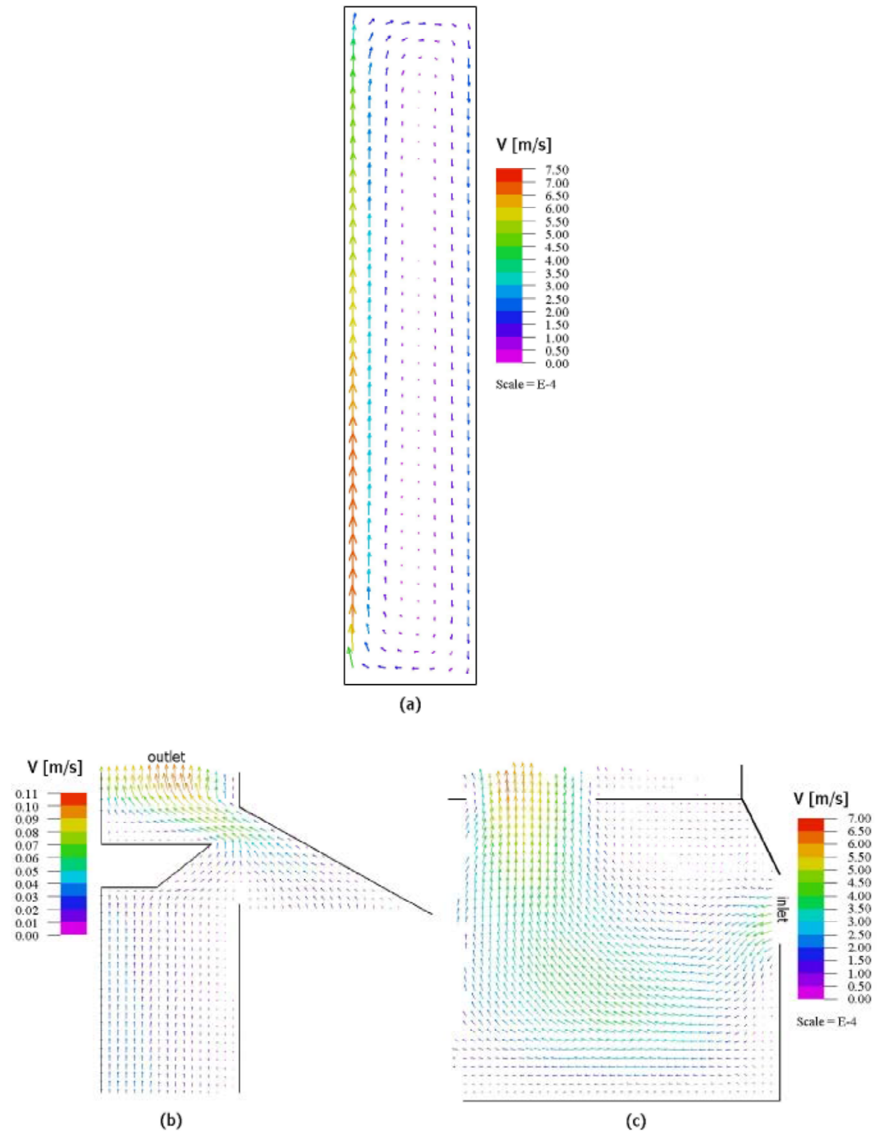


Fig. 4: Distribution of velocity vectors of water and gas in *case b*- with vent hood and without flue baffles (a) water tank (b) fired tube and (c) lower space with intake window

an eddy flow is formed within the water domain which occupies it volume completely. This vortex transfers the heat from the chimney wall to the upper and outer surface of the water tank which is displayed by deflection of the temperature field in that area.

In *case a*, the reduction of particles energy is high in the middle tube and also the outlet pressure is not so high. Therefore, for particles close to the water tank wall, gravity overcomes to buoyancy force and makes to return them downward (called a back draft), Figure 3(b). A back draft could interfere with proper venting of harmful gasses and could blow out the pilot light or burner. For this reason, a large and strong gas vortex is formed in the lower burner chamber which prevents the incoming air and thus the inlet cold air is quite weak, Figure 3(c). This vortex also prevents entering and reaching air needed for combustion to the burner. It has been observed that when the outlet pressure becomes more weak or negative, the inlet air flow becomes negative and the combustion products enters the room space from the air lower space. It is important to note that the combustion process creates by-product gasses such as carbon dioxide, carbon monoxide and nitrogen oxide. These gasses are harmful to breathe and need to be vented outside of the home. So, *case a* is not a safety configuration and dose not recommend.

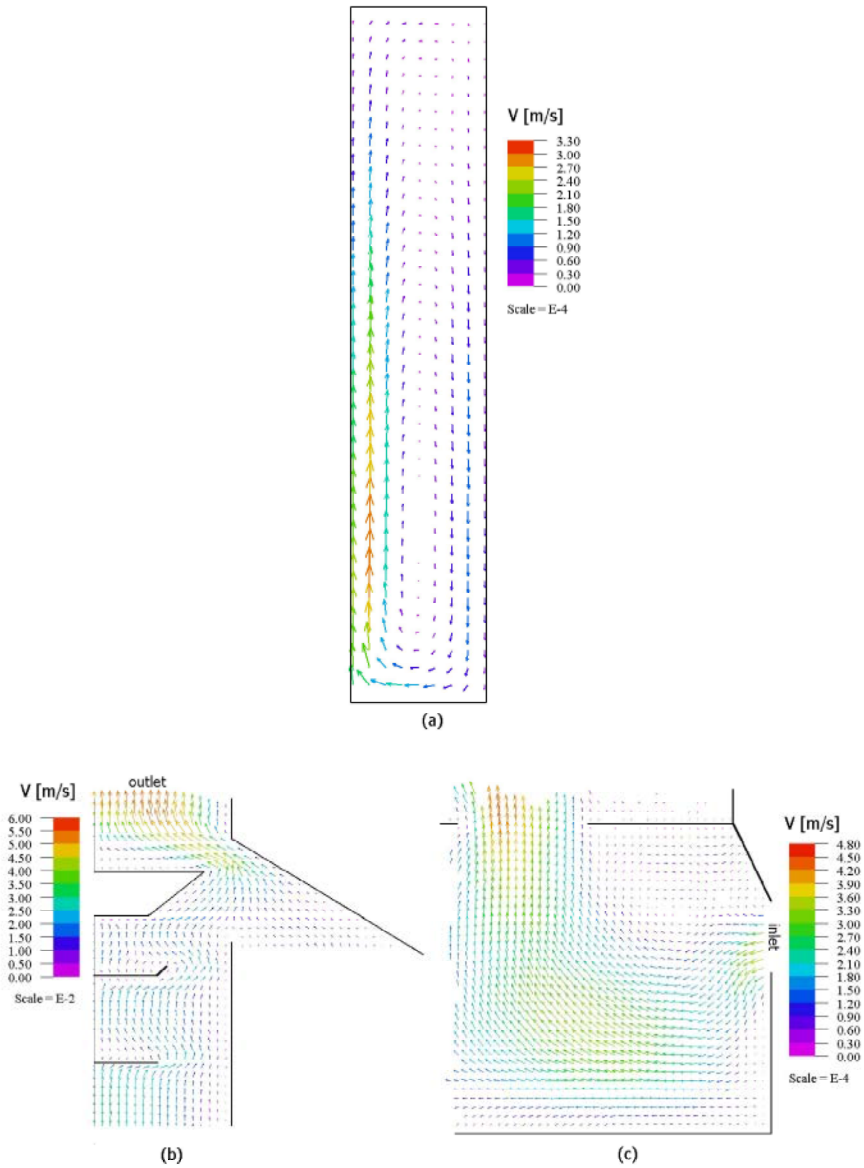


Fig. 5: Distribution of velocity vectors of water and gas in *case c*- with vent hood and flue baffles (a) water tank (b) fired tube and (c) lower space with intake window. Figure (5-b) is shown rate of cold air intake in the combustion chamber and in Figure (5-c) is shown zoom of the part of distribution of velocity vectors in fire tube and changing of direction of the combustion products that lead to delay in moving them

In *case b*, placing a vent hood at the exhaust flue gas makes to increase the exit of the combustion products from the fire tube and prevents the downward flow of these products into the flue too, Figure 4(b). In other words, it completely removes all products of combustion and vents gasses to the outside without condensation in the vent or spillage at the draft hood. Also the related problem of air needed for combustion is solved. For this reason, the formed gas vortex in the lowest chamber is quite smal and weak and so the inlet air from the intake window is markedly strong, Figure 4(c). Because of high outlet flow via the vent hood in this case, the transferred heat to the water is reduced to 540 *w* from 910 *w* in *case a*. For this resoan, the efficiency of this system is not so good.

In *case c*, three flue baffels and a damper are located in the fire tube in order to increase the delivered power to the water tank. Gas particles within the fire tube are diverted to the tank wall with collision to the flue baffles and so their energy can transfer to water simply and then

Table 1: Detailed information abou the total heat transferred to the water and out for three considered cases

Total heat transferred (units)	*Case a*	*Case b*	*Case c*
Output (*w*)	570	930	370
Water (*w*)	910	540	1020

move out with less energy in the fire tube, Figure 5(b). For this reason, these particles spend more time in the chimney and also a low difference of particles velocity as well as a less velocity boundary layer thickness is formed in that space. Therefore, energy is transferred rapidly to the adjacent layers. In this case, the maximum amount of heat can transfer into the water part (1020 *w*), Table 1. This is visible in Figure 2(c) which represents the highest temperature of water tank compared to other cases. In addition, the rate of cold air intake in the combustion chamber is quite high and strong, Figure 5(c) which can provide enough air needed for a right combustion.

CONCLUSIONS

From the above Calculation We Can Conclude:

- In *case a*, there is a downward gas flow in the flue and a strong vortex in the lower burner chamber. The formed gas eddy in the lower combustion chamber prevents from arrival of the necessary air for combustion.
- A draft hood positioned at the top of the flue (*case b*) prevents the backflow of air into the flue but the delivered heat to the water is not efficiently.
- Placing the flue baffles (*case c*) is caused delaying to exit of the hot combustion products and therefore makes the water heater more efficient and increases the heat output to the water.

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