ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

INVESTIGATION OF NATURAL CONVECTION IN SOLAR CHIMNEY WITH TRAPEZOIDAL SECTION TO IMPROVE COMFORT INSIDE SHIPPING CONTAINERS

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Abstract. *Shipping container is a cheap and easy way to build a internal environment. If occupied by people in warm climates, thermal discomfort usually occurs. The aim of this work is to investigate the use of solar chimney for natural ventilation inside containers. The cavity of the chimney, with trapezoidal cross section, is formed by placing a thermal insulating material against the lateral wall. The air enters the cavity from the internal environment through the bottom, flows to the top due to the heating of the metallic wall, and is dispersed in the external environment. An experimental apparatus was built with one cavity of a real container. The metallic wall was heated by electric resistors, in a range representative of solar incidence. Sensors of temperature and air velocity were positioned along the chimney. It was found that the chimney works even for low solar incidence. The air flow has a small increase between the smaller and the highest heat flux tested, from 6 to 9* m^3/h*. The increase of the temperature from the bottom to the top of the chimney is almost linear. In the middle between the metallic wall and the insulation, the air velocity is higher and the temperature is lower than near the walls. In the borders of the cavity, it was found higher temperatures with low velocities. Those results allow the application of the solar chimney in real situations, for industry and architecture.*

Keywords: *Solar Chimney, Natural Convection, Ventilation, Shipping Container, Thermal Comfort*

1. INTRODUCTION

Shipping containers are often used as a low cost solution for offices, stores and dwellings. They are extremely strong structures, made to transport heavy loads around the world. Because of rules of safety, they have a lifetime of twenty years. After that, they must be discarded and can not be loaded again, even if the structure is perfect. Because of that, during the last decades, the humanity is looking for new possibilities of use. The use as habitation is becoming more usual, specially because of the sustainability. Containers are big weathering steel boxes, resistant to corrosion. However, they are also excellent thermal conductors. That is why one of the major difficulties found in applications is to maintain the temperature in a comfort range.

In the north hemisphere, the major problem is the cold, so the basic solution is a good insulation and heating system. In tropical countries, the most common solution is the use of isolation and air conditioning system. In this case, the electricity is a vital part of the system and also a expansive solution in terms of energy. Once there are a huge amount of energy from natural sources like the sun and wind, passive techniques can be used to help solving the comfort problem. One of most effective solution is the use of cross ventilation, but we can not rely on it all the time. The sun is a source of energy that is available in a more constant way. The solar chimney is a technique that uses the energy of the sun to heat the air inside a cavity, resulting on its vertical movement due to the natural convection. The consequence is a suction in the base of the chimney. To increase structural strength, the container wall is shaped like trapezoids. The idea of this work is to study the possibility of creating cavities with this wall and use them as solar chimneys.

The behavior of the air in a solar chimney was the object of study of many authors. The main difference between their chimneys and the one proposed in the present work is the trapezoidal cross section. In all the works found, the cavity cross section is rectangular. Chen *et al.* (2003) experimentally studied the behavior of a solar chimney varying the size and the inclination of the cavity, with constant heat flux. Arce *et al.* (2009) studied a solar chimney in a external environment, heated by the sun. Sandberg and Moshfegh (1996) were one of the first authors to study a solar chimney. They found that the air flow is larger if the outlet of the chimney is upwardly open, and not laterally, as used in reals situation to protect from rain. The same authors also developed numerical simulations (Moshfegh and Sandberg, 1996).

This technique was also used in other studies. Gan (1998) showed with simulations that the chimney works best if the part to the internal environment is thermally isolated. Bassiouny and Koura (2008) included in their numerical model the internal environment, with a window in the opposite side.

2. EXPERIMENT

The experiments were developed in four different days. The temperature inside the laboratory varied from 19.0 to 22.3 °C on these days. The instrumentation was chosen to obtain the main data that describe the behavior of the natural convection inside the chimney. In order to simulate the heat provided by the sun, electric heaters were used.

A view of the cavity and the heater in the experimental apparatus is showed on Figure 1. The cavity is formed by lean an insulation material (expanded polyethylene, Neopor®, BASF) in the lateral wall. The metallic wall is 2.3 m height. The cross section of the cavity is trapezoidal, with the base equal to 208 mm, the top equal to 72 mm, and a height of 36 mm. The section area is equal to 5040 mm^2. The apparatus was covered with the same insulation material to minimize the heat losses to the ambient.

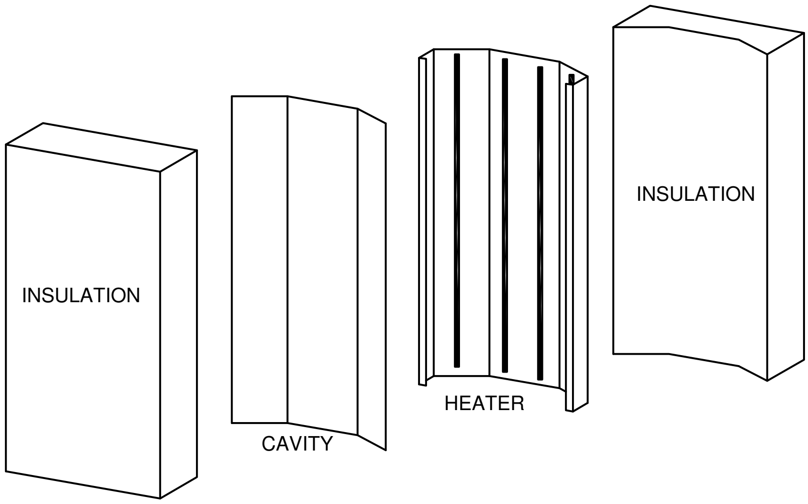

Figure 1. Main elements of the solar chimney.

The dissipation of heat through the metallic wall was made with four cylindrical electric heaters (Elbac), each with the length of 2.2 m and 9 mm of diameter. The generated heat flux was controlled by a potentiometer. The heaters were fixed by ceramic supports, in the wall where they are positioned on Fig. 1. A reflective adhesive was fixed on that wall to increase the uniformity of the heat arriving the cavity wall.

To protect the cavity from rain, the air outlet should be horizontal. The air inlet should also be horizontal, because it is close to the internal floor. Therefore, horizontal configurations were used for the inlet and outlet of the experimental apparatus, as showed on Figure 2.

The temperature and the air velocity were measured in several points of the cavity. Figure 2 shows their positions. Seven thermocouples were fixed on the metallic wall in different heights, equally spaced. Besides, some thermocouples were positioned in the same wall close to the border, to obtain the difference from the center. To obtain the temperature profile inside the cavity, nine thermocouples were set through the insulated wall, in three different heights. They could be freely moved between the metallic and insulated walls. The air temperatures in the inlet and outlet were also measured. Thermocouples type K were used (accuracy of ±2.2 °C).

The air velocity inside the cavity was measured in the same height (Fig. 2), with the probe (Testo 405-V1, accuracy of 0.1 m/s + 5% of the measured value) passing through the insulated wall, in three positions from the center to the left. The right side was considered to have the same velocities, due to the symmetry of the geometry. The probe was moved between the hot and the insulated wall. Each measured point was considered to represent an area, so the mean velocity was calculated. With the mean velocity, the mass flow was calculated with the temperature measured in that place. A volumetric flow with the entrance temperature was then calculated, so it represents the volume of air that is being removed from an internal ambient. The limit temperature of the air velocity sensor is 50 °C. In the highest measured heat flux, the temperature was higher than 50 °C, so the velocity was measured in a lower place, and subsequently corrected.

The temperatures of the external parts of the insulation were measured in several points with a infrared thermometer (Fluke 62max+, accuracy of ±1 °C). Those measurements were used to obtain the heat lost from the insulation. This heat was exclude from the heat generated by the electric heaters to determine the heat that achieve the cavity.

Seven situations were measured with different heat fluxes, until a value close to the highest solar incidence on the surface of the earth.

ISSN 2176-5480

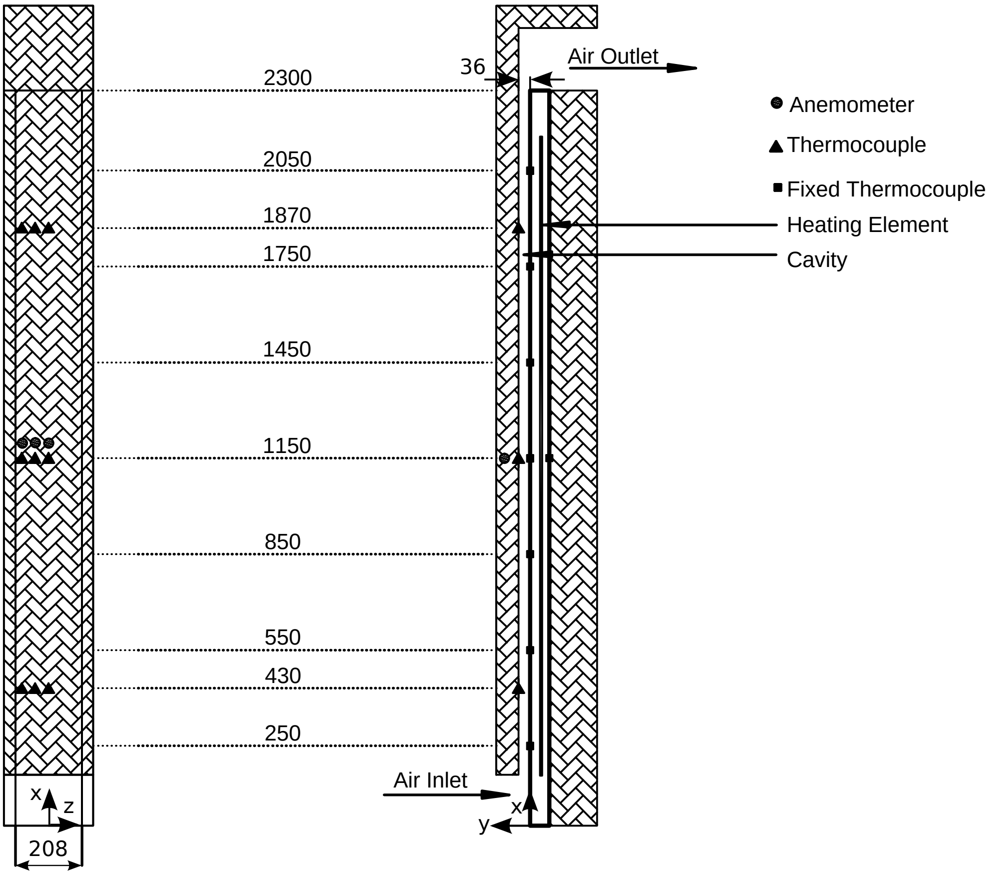

Figure 2. Experimental apparatus with the position of the sensors.

3. RESULTS AND DISCUSSION

3.1 Air flow

Figure 3 shows the air flow rate through the solar chimney, obtained for each of the measured situation. The value was corrected from the temperature of the measured point to the ambient temperature, thus it represents the amount of air being removed by one solar chimney.

The error bars are the measurement uncertainty. The value is large mainly due to the measurements of air speed.

An interesting result is that the increase of flow is small from the lowest to the highest value of heat flux. The flow increased 48%, while the heat flux increased 580%.

Small values of heat fluxes were also tested with the velocity sensor positioned in the center of chimney. It was observed that, even for small values of heat fluxes, the air velocity increases.

A equation for the volumetric flow rate was fitted to the data (r^2 = 0.75). It considers that the flow is null when there is no heat flux.

$$\dot{V} = 2.0\,q^{0.22} \tag{1}$$

where $\dot{V}$ is the air flow rate, m^3/h; and q is the heat flux, W/m^2.

An important value for thermal comfort application is the amount of air changes inside the container per hour. There are two typical shipping container standards, with lengths of 20 and 40 ft. The 20 ft container has 30 m^3 of internal volume, and folds in the lateral enough to create 20 solar chimneys. The 40 ft container has approximately the same proportion.

With a heat flux equal to 500 W/m^2, one cavity would have an air flow of 7.85 m^3/h, the whole lateral wall 157 m^3/h, resulting in 5.2 air changes per hour inside the container.

The air flow found in the present study is lower than the flows found by others studies, mainly because of its smaller cross-sectional area, equal to 0.005 m^2. Arce *et al.* (2009) obtained an average air flow of 177 m^3/h during a whole day; Gan (1998) obtained about 180 m^3/h with 400 W/m^2.

ISSN 2176-5480

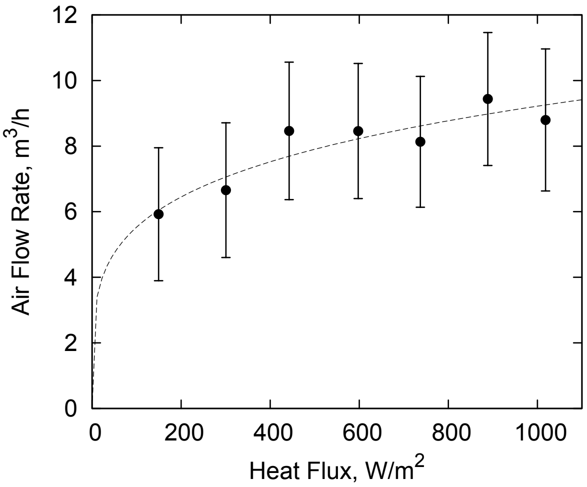

Figure 3. Volumetric flow rate through the solar chimney cavity for several inputs of heat fluxes, with error bars for the uncertainty and the fitted curve.

3.2 Air velocity

Figure 4 shows air velocity measurements in a horizontal plane in the middle of the chimney height, for different heat fluxes. The measurements were made in three distances from the center to the left of the isolated wall: 5 mm (Fig. 4a), 15 (Fig. 4b), and 70 mm (Fig. 4c). The position is showed on Fig. 2. The sensor was moved from the hot wall to the isolated wall. In the last measured position, the cavity deep is smaller, since it is closer to the border.

The velocity decreases from the Fig. 4a to Fig. 4c, that is, from the center to the lateral border.

The effect of increasing the heat flux in the velocity is clearly observed in the center of the chimney (Fig. 4a). The average velocity (for the three points) increased about 0.4 m/s from 300 to 890 W/m^2, in other words, the velocity increased 81% while the heat flux increased 196%. A lower dependency of the heat flux on the velocity is found on Fig. 4b. The average increase of velocity was 60%, for the same heat flux increment. In this position, the velocity does not seem to depend on the intermediate heat fluxes. In the position closer to the border, this non-dependency is also observed. The velocity is about 0.4 m/s for all measured heat fluxes. Those observations might be explained by the effect of the shear stress from the walls. The larger distance between the metallic wall and the insulation is only 36 mm.

3.3 Hot wall temperature

Figure 5 shows the metallic wall temperature in equally spaced points along the height, for all the tested heat fluxes. The relation is approximately linear, except for the entrance region. The slope increases with the heat flux. The linearity found in the metallic wall is related to the increase of the air temperature inside the chimney and the heater, the wall conduction, and the heater radiative heat transfer.

3.4 Air temperature

Figure 6 shows the air temperature from the metallic wall to the insulated wall, for two heat fluxes (300 e 740 W/m^2). The measurements were made in three heights from the bottom: 0.25, 1.15 and 2.05 m. Each graph shows the air temperature for different positions from the center to the lateral border (Fig. 2).

The temperature is higher near the walls. The lowest temperatures occur near the hot wall in Fig. 6a and Fig. 6b. In the lateral border of the chimney, where the distance between the walls is smaller (Fig. 6c), the air temperature is almost constant between the walls. The air temperature in the border is higher than the other measured positions, for the same height and heat flux.

The air temperature increases with the height and heat flux. In the entrance region (height of 0.25 m), the temperature is very close to the ambient temperature. The highest air temperature found is about 40 °C higher than the air temperature.

4. CONCLUSION

In the present work, the behavior of a solar chimney constructed with a lateral wall of a shipping container is studied, with different heat fluxes. The cavity of the chimney has a trapezoidal cross-section. It was found that the chimney works even for low heat fluxes. A large increase of the air flow was found in the lowest heat flux measured. After that, the air flow is less affected by the increase of the heat flux. The air volumetric flow rate (in m^3/h) removed from an internal

ISSN 2176-5480

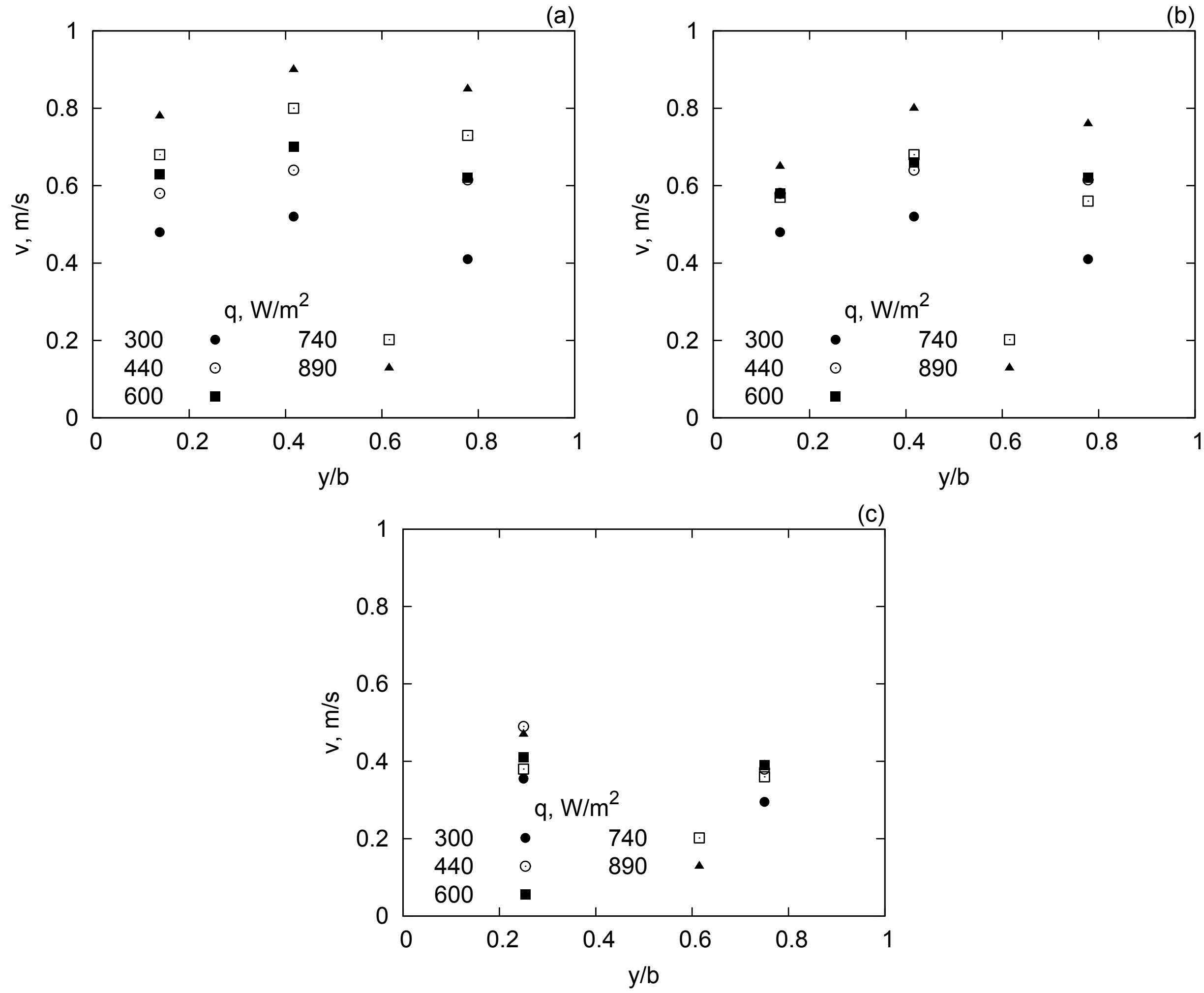

Figure 4. Air velocity from the metallic hot wall ($y/l = 0$) to the isolated wall (y/l), for z = 5 mm (a), z = 15 mm (b), and z = 70 mm.

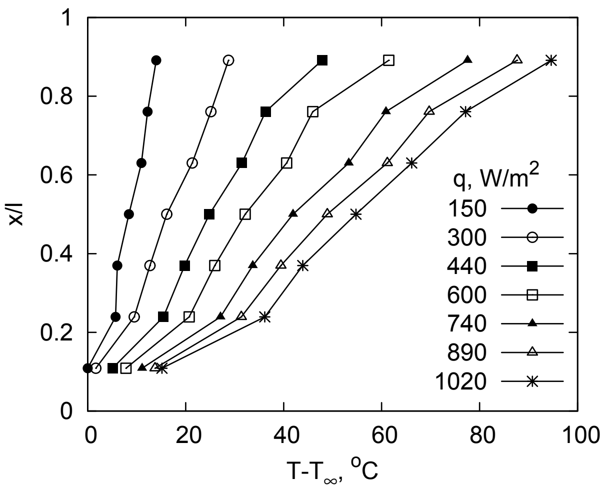

Figure 5. Measurements of the difference between the metallic wall temperature and the ambient temperature along the chimney height for several heat fluxes (l=2.3 m). The connection between the points are only to facilitate visualization.

ambient by one cavity depends on the heat flux (in W/m^2) by the expression $\dot{V} = 2.0\,q^{0.22}$. In the middle between the hot and the insulated wall, the air temperature is lower and the velocity higher. The velocity is smaller in the border of the trapezium and seems not to be influenced by the heat flux changes. In this place, higher temperatures were found.

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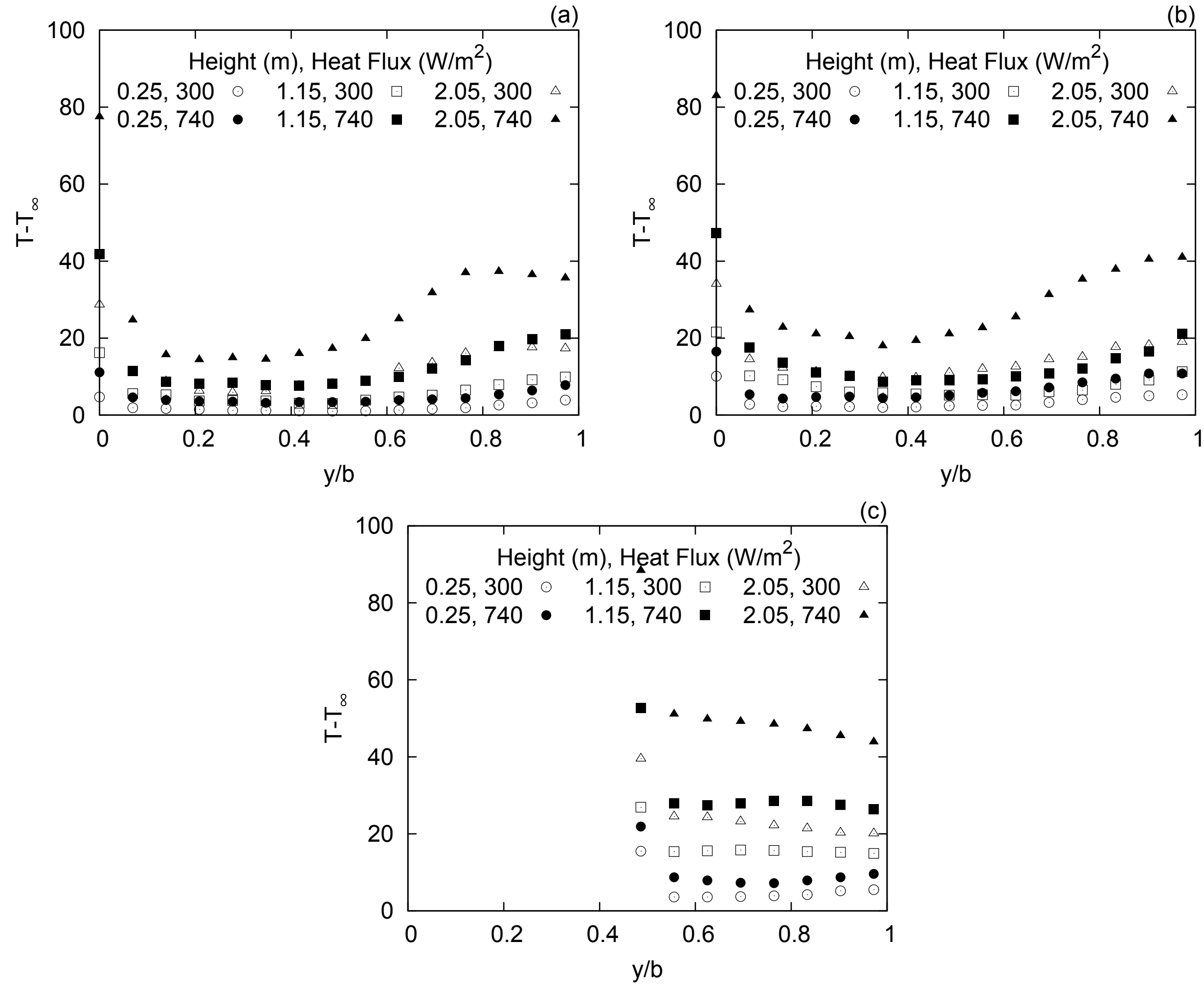

Figure 6. Difference between air temperature inside the chimney and the ambient air temperature, for some heights and two heat fluxes, from the hot to the isolated wall (b=36 mm).

5. ACKNOWLEDGEMENTS

The authors are grateful to Contain'it and to Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for the support.

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7. RESPONSIBILITY NOTICE

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