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Development of a Compact Combustion System (CCS)

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This work discusses a novel concept in the developing of furnaces and combustion chambers. It uses special cooling techniques dispensing the use of insulating and refractory bricks, leading to combustion chambers light and compact. The conventional layers of refractory and insulating bricks mortar are substituted by a wall consisting of two parallel metallic plates with air between them. The technique uses small slots calculated in such a way that the heat is extracted from this space between the plates by forced convection. For the needed calculations the similarity methods applied to convection heat transfer processes were used (leading to local film heat transfer coefficient estimates based on Nusselt number expressions for given Reynolds and Prandtl numbers validity ranges), as well as a radiation shielding calculation method was performed to effectively reduce the radiation heat transfer among the surfaces. (the calculation of the shield temperature leading to the heat flux calculation).

Keywords: combustion chambers, compact combustion chamber, radiation shields

INTRODUCTION

It will be discussed here a novel concept in the developing of furnaces and combustion chambers. This concept uses special cooling techniques which make possible to dispense the use of insulating and refractory bricks, leading to combustion chambers light and compact. This procedure can be used in a fabrication plant, where a furnace is built with the walls cooling being performed by air bled from the blower in the combustion feeding loop. This will lead to a much cleaner operation with less pollution, for the combustion air and the combustion process will be better controlled. Besides, a less expensive and more compact system can be achieved. The next stage of this development, will be the placing of the heat exchanger next to the combustion chamber, using the working fluid to perform the walls (plates) cooling, leading to a further system compacting increase (i.e., for the set consisting of the furnace plus the heat exchanger). This might bring an overall volume reduction by a factor 15 to 20 times from the original volume.

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DESIGN STRATEGY

Usually the inner wall of a furnace consists on a layer of refractory bricks and one or two layers of insulating bricks plus the proper fixing mortar, this leading to an overall mean thickness of around 50 cm. All this is substituted by a wall consisting of two parallel metallic plates separated 5 to 10 cm from each other, with air between them.

This technique uses small slots calculated in such a way that the heat is extracted from this space between the plates by forced convection. This air taking the heat away by forced convection is provided by the blower responsible for the combustion air feeding so that part of it is bled to be used for cooling the combustion chamber.

Notice that, as the wall cooling air is heated prior to entering the combustion chamber, then there is a minimum of heat loss to the environment, besides there is the fact that this heated air entering the combustion reaction will allow the burning of leaner mixtures, which decreases the mean furnace operating temperature but not the global energy it delivers, thus reducing the pollutant generation. Water can also be used for wall cooling and or as a processing fluid. In this case the heated mixture of water/working fluid may go into a boiler for steam generation or straight into the process, saving energy.

WORKING EQUATIONS

The similarity methods applied to the convective heat transfer in the turbulent flow of liquids and gases yield [1]:

$$\mathrm{Nu_f} = 0.021\mathrm{Re_f^{0.8}}\mathrm{Pr_f^{0.43}}\left(\mathrm{Pr_f}/\mathrm{Pr_w}\right)^{0.25} \tag{1}$$

where Nu, Re and Pr are the flow Nusselt, Reynolds and Prandtl numbers respectively, the terms with the subscript f referring them to T_f, the mean fluid temperature, taken as a reference temperature, and the subscript w refers to T_w, the wall temperature. The reference geometric dimension is the chamber diameter, d, or the distance between plates, l, both taken in meters. The above equation can be used for Re > 10^4 and $0.7 < \mathrm{Pr_f} < 2500$ and for temperatures below the liquid boiling point [1].The local heat transfer coefficient, α, (i.e., the film coefficient) is given by

$$\alpha = \frac{\mathrm{Nu_f}\lambda_f}{\mathrm{d}} \tag{2}$$

where λ_f is the thermal conductivity. Hence Q, the total rate of heat being transferred by convection, can be written

$$Q = \alpha F \Delta T \tag{3}$$

where F is the transfer surface. If two parallel surfaces 1 and 2, having different temperatures T_1 e T_2, are arranged at a small distance from the other, heat is exchanged between them by radiation. The first surface emits rays to the other, and the latter partly absorbs and partly reflects these rays. In this case only the first reflection is of appreciable importance, since the amounts of energy repeatedly reflected are so small that may be neglected. The total radiation of the first surface consists of its inherent radiation $C_1(T_1/100)^4$ and the reflected radiation emitted by the second surface is $E_2(1-A_1)$ i.e.,

$$E_1 = C_1\left(\frac{T_1}{100}\right)^4 + E_2(1-A_1) \tag{4}$$

and by analogy,

$$E_2 = C_2\left(\frac{T_2}{100}\right)^4 + E_1(1-A_2) \tag{5}$$

Recalling Kirchhof's Law, the net rate of radiating heat between two plane parallel gray surfaces of area F can be written as

$$Q = \frac{1}{\frac{1}{C_1}+\frac{1}{C_2}-\frac{1}{C_0}} F\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \tag{6}$$

where C_0 = 5.67 W/m^{2}K^4 is the radiation factor. Calling $C_{1-2} = \frac{1}{\frac{1}{C_1}+\frac{1}{C_2}-\frac{1}{C_0}}$, multiplying and dividing it by C_0 = 5.67 and using $\varepsilon = \frac{E}{E_0} = \frac{C}{C_0} = \frac{C}{5.67}$, where E_0 is the emissive power of a black body, then C_{1-2} can be expressed in terms of the emissivity, ε, or of the reduced emissivity, ε_{reduc} , as shown next:

$$C_{1-2} = \frac{5.67}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1} = 5.67\varepsilon_{reduc} \tag{7}$$

then

$$Q = 5.67\varepsilon_{reduc} F\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \tag{8}$$

The balance between radiation and convection heat transfer rates between consecutive plates yields

$$5.67\varepsilon_{reduc}F_1\left[\left(\frac{T_1}{100}\right)^4-\left(\frac{T_2}{100}\right)^4\right]=\alpha(F_2T_2+F_1T_1) \tag{9}$$

where F_1 and F_2 are the areas of plates 1 and 2 which might be equal or not. Hence the pre-defined dimensions can be used with a safety margin.

RADIATION SHIELDING

A way of decreasing the radiation exchange between surfaces is employing highly reflective materials. An alternate method to do so is through the use of a shield between those surfaces. As it is well known, the expression for the reduction in radiant heat transfer between two infinite parallel gray planes, 1 and 3 having the same area, A, when a thin parallel gray sheet, 2, of very high thermal conductivity is placed between them is given by [2]

$$\frac{Q_{12}}{Q_{13}}=\frac{\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_3}-1\right)}{\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1\right)+\left(\frac{1}{\varepsilon_2}+\frac{1}{\varepsilon_3}-1\right)} \tag{10}$$

This is the ratio of radiant energy transfer with a shield to that without one. If all three surfaces have the same emissivity, this fraction is one half. Then the shield temperature can be written as

$$T_2^4=\frac{1}{2}\left(T_1^4+T_3^4\right) \tag{11}$$

Multiple shields are even more effective [2].

ESTIMATING THE THICKNESS OF THE COMBUSTION CHAMBER WALLS

The limiting strength to Fatigue, S_e is defined as [3]:

$$S_e = S_{n'}.K_a.K_b.K_d \tag{12}$$

Where K_a is the surface factor related to the material finishing, K_b is the size factor related to the piece dimensions, K_d is the temperature factor related to the piece operation under high temperature and $S_{n'}$ is fatigue strength limit related to cyclic loading [3].

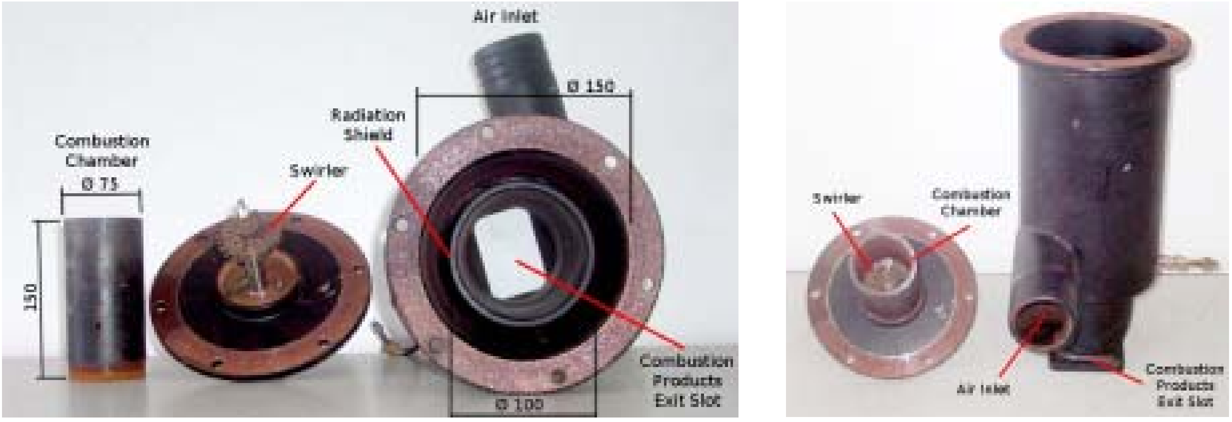
Recalling that the theory for thin walled vessels under internal pressure [3] yields the relation:

$$t_c=\frac{p_1 d_m}{2S_e} \tag{13}$$

Where t_c is the wall thickness, p_1 the internal chamber pressure, d_m the vessel mean diameter and S_e the yield stress of the vessel material. Assuming fatigue to be the most critical aspect and choosing the following values for the above constants [3] $K_a = 0.7$ (assuming surface machine finishing), $K_b = 0.85$ (value adopted for pieces with diameter between 7.6 and 50 mm). The temperature factor, K_d is obtained from the following equation valid for steel, for temperatures above 71^{o}C. Then,

$$K_d=\frac{344.4}{273.15+T} \tag{14}$$

CONCLUDING REMARKS:



a b

Fig. 1 – Compact combustion chamber prototype: **a** –exploded view; **b** – partial assembling

A small prototype was built (Fig. 1) and performed quite well. This led to use this technique in a fabrication plant, where a furnace was built using the procedure described above, the walls cooling being performed by air bled from the blower in the combustion feeding loop. This furnace turned out to be 10 times smaller than the original furnace (in volume), leading to a much better space allotment, besides offering a much cleaner operation with less pollution, once the combustion air and the combustion process came under much better control. This way a less expensive and much more compact system (which could actually be moved around in the facility) was achieved. The next stage of this development, which will be the placing of the heat exchanger next to the combustion chamber, using the working fluid to perform the walls (plates) cooling, is expected to lead to a further system compacting increase (i.e., for the set consisting of the furnace plus the heat exchanger). It can be estimated that this will bring an overall volume reduction by a factor 15 to 20 times from the original volume. This facility will have wheels for easy transportation.

Finally notice also that water can also be used for wall cooling and or as a processing fluid. In this case the heated mixture of water/working fluid may go into a boiler for steam generation or straight into the process, saving energy.

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