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An alternative solution for insulating a burning chamber with high temperature walls

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Abstract. Usually, the industrial halls, who are in most cases poorly insulated and have high permeability, are heated with hot air generators or convecto-radiators. Using convecto-radiators is improper and hot air generators, although it is more appropriate, it consumes a very high amount of energy. This paper continues the topic discussed in a previous article [1] in which we presented an alternative heating solution to the existing ones. The heating system mentioned uses an environmentally friendly and cheap fuel (biomass). This paper presents an alternative solution to insulate a burning chamber (BC) with high temperature walls that uses pellets as fuel. This technical solution has the benefit of supplying heating agents to various types of heat consumers and to optimize the construction costs through the materials used. The BC is design with external ribs on here longitudinal direction. For insulating and cooling the BC, a metallic case was design through which atmospheric air is circulated. Three constructive solutions of BCs were analysed. The paper presents the modelling results of the constructive solutions and the calculation method. The calculation was made applying the physical laws that govern this type of heat transfer and was made with discretization segments. Determining the parameters of each segment will allow the user to optimize the equipment design. The main purpose of the study is to conceive an alternative technical solution for insulating the BC, that should be cheaper, easy to implement and able to prepare a second thermal agent for heating.

1. Nomenclature

A_{air} – Air area;
$A_{f.g.}$ – Flue gas area;
dx – A segment discretization (s.d.);
H_{rib} – Rib height;
T_{air} – Air temperature;
T_{ai}^{X} – Air inlet temperature for s.d.;
T_{ao}^{X} – Air outlet temperature for s.d.;
$T_{f.g.}$ – Flue gas temperature;
T_{fgi}^{X} – Flue gas inlet temperature for s.d.;
T_{fgo}^{X} – Flue gas outlet temperature for s.d.;
T_{is} – Insulation temperature;
T_{met} – Inner temperature of the metal sheet of the B.C.;
T_{wall} – Inner temperature of the refractory insulation;
T_{w}^{X} – Tmet for s.d.;
$S_{flow\ air}$ – Channel section were atmospheric air flows;
S_{smooth} – Smooth surface on the side of flue gas;
S_{ext} – Exterior surface with ribs of the burning chamber;
Q_{fgi}^{X} – Flue gas inlet heat flux for s.d.;
Q_{fgo}^{X} – Flue gas outlet heat flux for s.d.;
Q_{cv}^{X} – Convective heat flux for s.d. transmitted to wall;
Q_{r}^{X} – Radiated heat flux for s.d. transmitted to wall;
Q_{T}^{X} – Total heat flux for s.d. transmitted;
Q_{T} – Total heat flux transmitted, radiation and convection;
Q_{BP} – Total heat flux transmitted from the burner;
δ_{rib} – Rib thickness;
δ_{is} – Insulation thickness;
δ_{met} – Metal thickness;

2. Introduction

Many industrial buildings are poorly insulated or not insulated at all. Also, the large glazed surfaces that are often implemented in such halls contribute to the high energy demand for heating. Another problem is the high number of fresh air exchanges due to large openings or construction leaks, or due to the need to remove pollutants. These air exchanges are usually much higher than the ones required to provide the minimum number of air exchanges. These circumstances can put engineers in a difficult situation regarding the proper heating system that they should implement. The common technical solution used is a fossil fuel equipment coupled with hot air generators [2]. Another solution used is a fossil fuel equipment but coupled with convecto-radiators [2]. Although the hot air generators can be more proper to use, this technical solution still presents the disadvantage of high energy consumption. A way of approaching this problem, regarding the heating system, is to:

- change the fossil fuel with one that is cheaper and more environmentally friendly;
- replace the heating system that uses intermediate agent (convecto-radiators or hot air generators) with a direct heating system (like radiation);
- replace the centralized heating system with a decentralized one, in order to eliminate the heat losses on the primary thermal transport network.

The issues that arises when it comes to implement those solutions are:

- the difficulty of removing the presence of the intermediary agent;
- the problem of the presence of high temperatures (above 750°C) when using quasi-adiabatic burning chambers (BCs) coupled with radiation systems;
- the impossibility to connect different types of consumers (coupling convecto-radiators and radiation systems) to the same BC;
- significant increase of costs, complicated logistics for fuelling, for maintenance and surveillance of the burners when using small heating subsystems, due to the impossibility of connecting different types of consumers to the same BC.

All those difficulties will lead to the choice of a classic solution, a single system with fossil fuel.

In previous studies [3, 4] we presented different approaches to deal with those problems while a complete system was presented in this paper [1]. That heating system [1] is designed with a BC that uses pellets and provides heating agents for a radiation equipment, for a convecto-radiator equipment and for a thermal tube heat recovery equipment. While both radiation and convecto-radiator equipment's are used for heating the hall, the entrances or the large glazed areas, the thermal tube heat recovery is used to prepare hot water for consumption. So, that solution [1] can provide simultaneously heating and hot water. That system was part of a dissertation thesis study. In this paper will be presented the constructive model of the BC from that study. An alternative technical solution for insulating a BC can be seen in this constructive model, a solution that will allow to create a second agent for heating. This solution provides a more economical option to insulate the BC, while fulfilling the purpose of limiting the heat transfer and maintaining a safe temperature on the surface of the exterior walls. This study presents a calculation method that allows the determination of parameters like BC wall temperatures, insulation wall temperatures, hot air temperatures, aeraulic parameters of the hot air and so on. Also, the study analyses how varying technical aspects of the solution will influence those parameters. The main purposes of this research are:

- to create an alternative solution for insulating the BC (a cheaper solution, that can produce a second heat agent, and which can be easily implemented);
- to analyse this solution in order to determine how the design can influence parameters like wall temperatures, hot air temperature and pressure loss.

3. Methods

3.1. Calculation method

The methodology used was presented in previous studies [4-6] but various modifications have been made in order to be used for this study. The calculation method is an iterative one and it closes when the errors are lower than the ones admissible (for example, between 0.01÷1% for temperature). These represents the calculation errors and not the errors generated by the criterial equations of the heat and mass transfer, errors which reflect the differences between theory and practice. One of the main purposes of this numeric calculation is to determine the wall temperature for the BC. The wall temperature of the BC influences the refractoriness of the material used, which is in general steel. Knowing the wall temperature and adjusting the refractoriness accordingly has economic consequences. For determining the wall temperature of the BC, the radiation calculation method was coupled with a classical convection method used for gases with temperatures above 400°C. This method of calculation is extensively verified in practice because it is used as a basis for dimensioning the high temperature convective equipment's (≥400°C). The calculation method used has a supplementary convective coefficient which is the equivalence, in terms of convection, with the radiant heat flux. The convection phenomenon at the wall, generated by the flue gas flow in the furnace, is added to the radiation effect (his equivalent in convection terms). An adjustment was made to the calculation method by correcting the absorption coefficient with the emissivity component of the flame. So, this methodology takes the absorption coefficient of the "flame - flue gas" environment, from the classical calculation of a furnace (BC), and the radiation heat flux in terms of convection, from the convective equipment's calculation [7-10]. The operational scheme of the calculation program can be seen in Figure 2. This method represents an alternative to the classical method used for dimensioning a BC. The classical methodology is based on the criterial equation of Boltzmann invariants (Boltzmann – θf, dimensionless), without calculating the wall temperature, but only the theoretical burning temperature and the flue gas temperature at the exit section of the furnace (BC).

In order to control the surface temperature for any BC, a thermal insulation is used. Because of the high temperatures reached (>750°C) in this type of BCs, the thermal insulation has significant thicknesses and is often expensive. Also, high temperatures lead to high refractory materials (steals) and this translates into high costs. In addition to the role of limiting heat transfer, another main role of the insulation is to achieve a safe temperature on the exterior surface of the BC in order to avoid possible human accidents. The heat transfer parameters for the proposed method of insulating the BC can be seen in Figure 1. Figure 1 shows also the temperature drop from the furnace (BC) environment to the hot air agent.

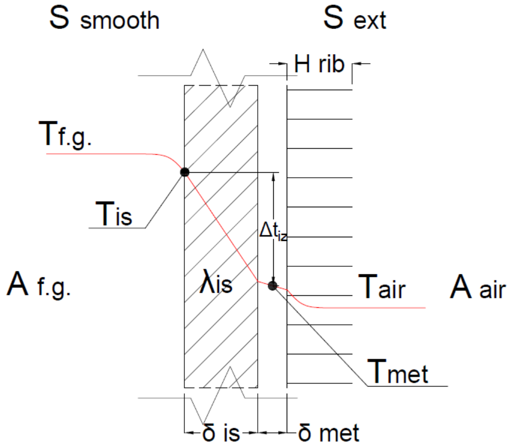

Figure. 1 Schematic temperature variation and heat transfer parameters between two environments

The operational scheme seen in Figure 2 is a simplified version of the logic scheme of the calculation program, but it contains the main stages of calculation and the loops calculation, as well as their defining parameters. As we can observed, the operational scheme references to the global calculation and not to the discretization calculation, but it was chosen as a presentation because it expresses in a clear and concise form all the elements of modelling and of the calculation of the program.

The longitudinal ribs welded on the outside of the BC are seen in the right side of Figure 1. The ribs have the role to improve the heat transfer. The surface that is defined as Ssmoth represents the inner surface of the BC, while the Sext represents the heat transfer surface of the ribs (mounted on the exterior surface of the BC). Using a good ratio between their geometric characteristics (height, thickness) and their number (the distance between them) will lead to an improvement of the heat transfer. The calculation is iterative and uses discretization segments which is useful because it offers the possibility to determine, for each segment, the parameters needed to optimize the design of the equipment. Thus, this type of calculation allows the user to modify parameters in order to obtain a good technical–economical ratio. A discretization segment of the BC is presented in Figure 3. Here we can see the parameters and the fluxes involved in the heat transfer between the two environments. All of them were considered in the calculation methodology.

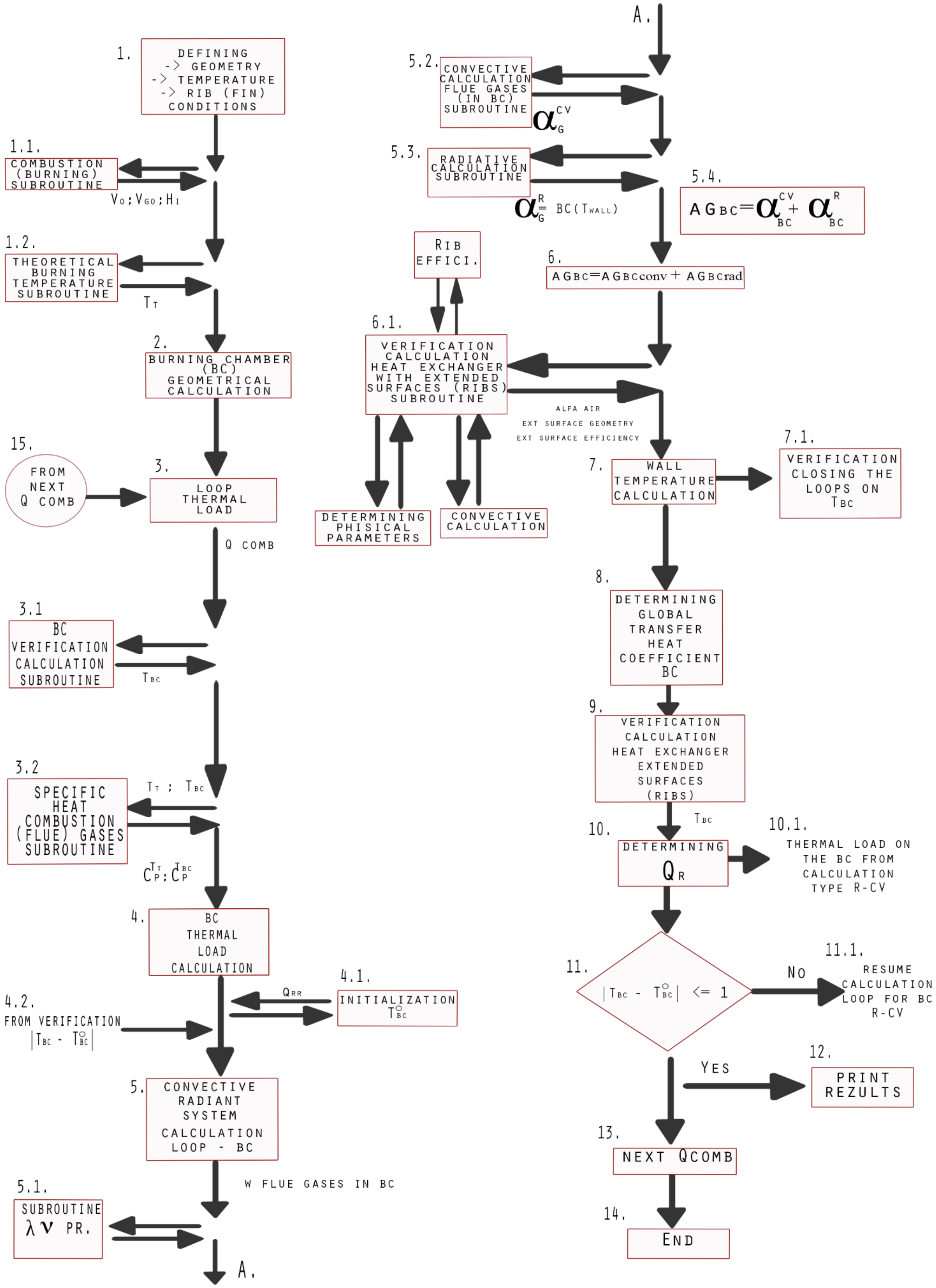

Figure. 2 Operational scheme of the calculation program

The heat fluxes seen in Figure 3 can be described by a balance equation, based on the laws of conservation, between the heat flow entering the segment dx, Q_{fgi}^{x}, and the output heat flow from that segment dx, Qfgox, plus the heat transmitted to the heated air, Q_{T}^{x}, as:

$$Q_T^x = Q_{cv}^x + Q_r^x; \quad (1)$$

$$Q_{cv}^x + Q_r^x = Q_{fgi}^x - Q_{fgo}^x; \text{ or} \quad (2)$$

$$Q_{fgi}^x = Q_T^x + Q_{fgo}^x \quad (3)$$

$$Q_T^x = f(T_{fgi}^x, T_{fgo}^x, T_w^x, T_{ai}^x, T_{ao}^x) \quad (4)$$

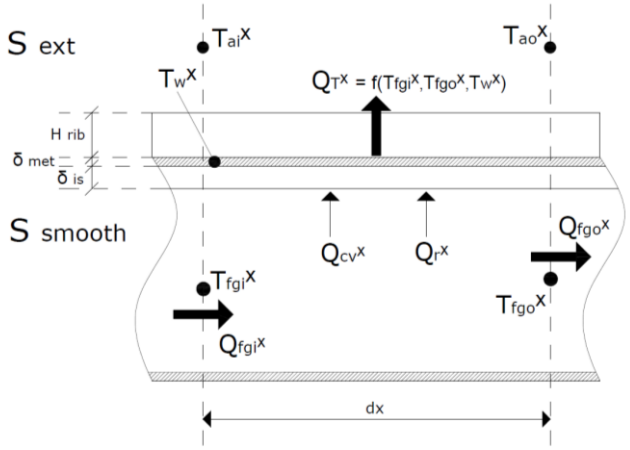

Figure. 3 A BC discretization segment with parameters and heat fluxes

At the same time, in addition to the parameters and heat fluxes specified above, individually, for each segment of discretization is determined the convective coefficients, the radiation coefficients, the flow velocities, the physico-chemical characteristics of the agents, the efficiency of the extended surfaces (ribs) and so on

3.2. Burning chamber geometry

The system presented in Figure 4 has the usual components found in a heating system that uses pellets (tank, pellet screw, burning chamber and so on). The burning chamber is considered to have one or more Stocker burners, which represents the most encountered solution for burners that uses pellet fuels. In Figure 4, which shows the technical solution of the BC, we can see that the flue gas formed must travel two baffles before exiting. The role of the first baffle is to generate extra turbulence to properly mix the excess air and the incomplete combustion elements that remained. The second baffle is to make a coarse dust separation by inertia. The BC has a metallic casing at a distance of several millimeters, making a channel between the BC and the metallic insulation through which atmospheric air is circulated by a fan.

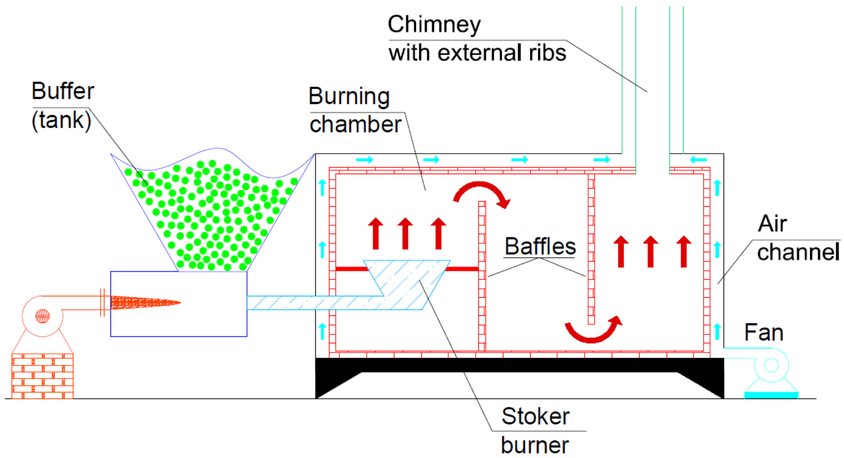

Figure. 4 Simplified combustion chamber scheme with the Stocker burner, two baffles and a metallic casing

This solution is designed to insulate the BC in a more economical way and to produce a second heating agent, hot air. The BC has a parallelepipedic shape, with external ribs welded longitudinally (Figure 5) and is placed on the ground with a normal insulation at the bottom. As an imposed condition, the exterior temperature of the metal case (Tmet) must have maximum 150°C (to allow safe insulation with cheap materials, like mineral wool). Adjusting parameters like the thickness of the refractory insulation, the heat coefficient of the refractory insulation, the section of the channel created between the BC and the metallic casing, the rib dimensions, the distance between the ribs and the length of the BC will allowed to achieve the temperature goal. Thus, studying and adjusting these parameters allows the user to adjust the flue gases temperature, the hot air temperature, the metallic casing temperature, maintaining the aeraulic parameters at acceptable values and so on, depending on the purpose pursued.

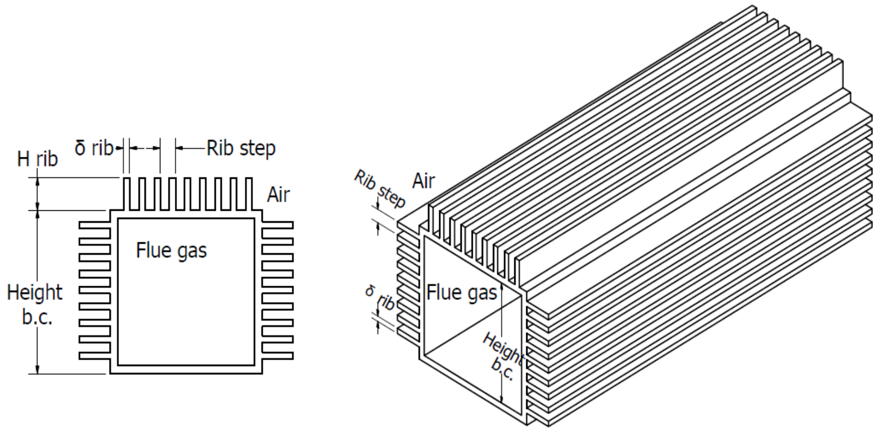

Figure. 5 BC geometry: front section and 3D isometric view, without the metallic case

Typical geometries for this type of BCs were used in this calculation. Three solutions were analyzed, modifying parameters like:

- the dimension of the BC (length, width);
- the thickness of the refractory insulation and its thermal transfer coefficient;
- the height of the channel where the atmospheric air flows.

As a rule of thumb in current practice, the length of the burning chamber is approximately one and a half to three times its width (1.5÷3*width ≈ length). The atmospheric air that flows through the channels, for all the solutions, was considered 500 m³N/h. The fluid flow, flue gas and atmospheric air, were in a parallel flow. The burner power was 100 kW, representing an average power for such heating system. The same calculations can be performed at higher or lower thermal powers. More technical details of the BC can be seen in Figure 6, where a front section view of the BC with all the geometrical elements is showed. This view includes the temperature notations for each material and parameter.

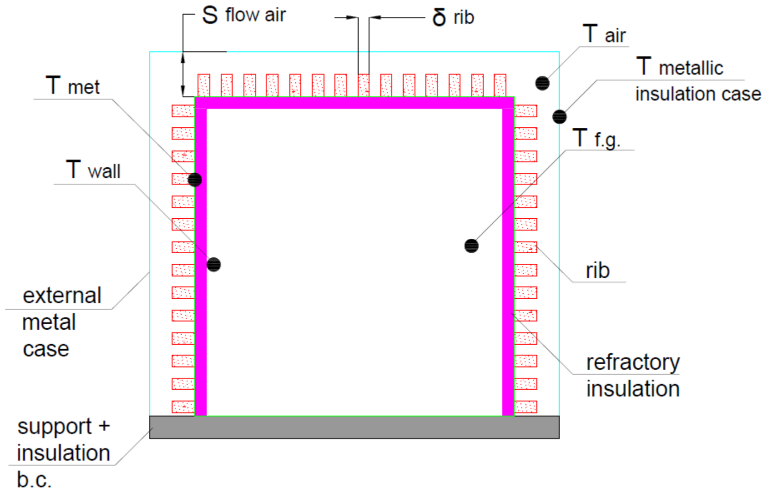

Figure. 6 BC front section with geometrical elements and parameters

3.3. Burning chamber parameters

The constructive parameters that defines each BC can be seen in table 1.

Table 1. Constructive details of the BCs

Segment	M.U.	Construction		
		Type1	Type2	Type3
Width BC	mm	700	1000	1000
Height BC	mm	700	1000	1000
Length BC	mm	2000	1500	1500
Channel height	mm	300	200	200
Refractory insulation thickness	mm	50	65	100
Refractory insulation transfer coefficient	W / (m*K)	0.1	0.15	0.15
Flow section	mm	63	60	60
Equivalent hydraulic diameter	-	5.75	3.92	3.92
Rib height	mm	50	50	50
Rib thickness	mm	5	5	5
Rib step	mm	25	25	25
Sheet thickness	mm	4	4	4

The BC parameters selected, like the dimensions, the refractory insulation thickness, the insulation transfer coefficient, and so on are in the usual ranges for this type of equipment. Initial calculation conditions chosen for all three solutions are presented in Table 2.

Table 2. Initial calculation conditions

Parameter	M.U.
Burner power	100 [kW]
Flue gases temperature	1580 [°C]
Atmospheric air flow	500 [m^3_N/h]

4. Results

An important observation that we must refer to is the discretization segment length of the BCs. All three BCs were divided in 10 segments. If for the first solution, the segment length is 200mm, for the second and the third solution the segment length is 150mm. We must keep this in mind when comparing the parameters at the same segment of discretization because a 10-segment discretization for the last two cases (Type 2 and 3) is equivalent with a 7.5 segment discretization for the first case (Type 1), see ratio in Table 3. When values were compared in this paper, for different parameters, they were extracted from a length of 1500 mm from all three solutions.

Table 3. Discretization segment length

Discretization segment	Length of the BC [mm]			
	Type 1	Type 2	Type 3	Ratio
1	200	150	150	0.75
2	400	300	300	1.50
3	600	450	450	2.25
4	800	600	600	3.00
5	1000	750	750	3.75
6	1200	900	900	4.50
7	1400	1050	1050	5.25
8	1600	1200	1200	6.00
9	1800	1350	1350	6.75
10	2000	1500	1500	7.50

First modelling results compared were the flue gas temperature variation and the atmospheric air temperature variation. These parameters allow an overview of the heat transfer and, depending on the purpose, allow the optimization of the technical solution to obtain the desired temperatures for the thermal agents. Flue gas temperature variation, on segment discretization, are seen in Figure 7.

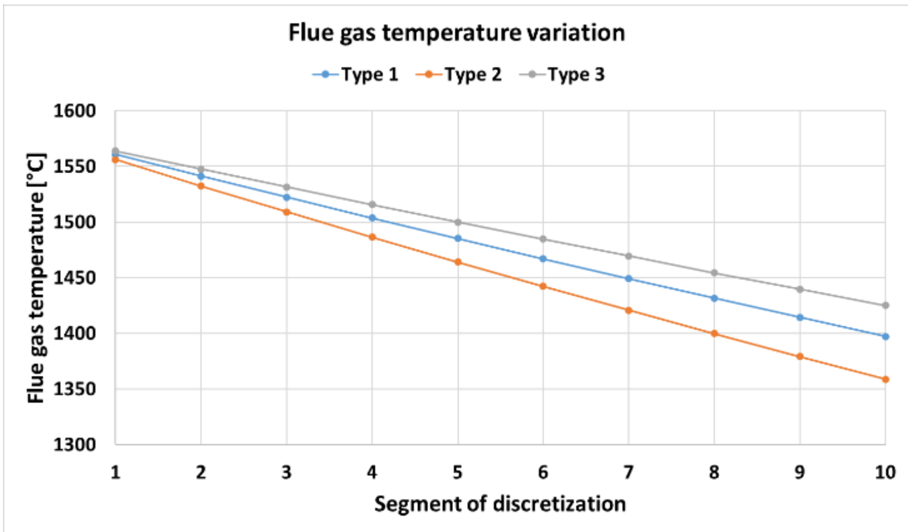

Figure. 7 Flue gas temperature variation ($T_{f.g.}$)

The temperature variation of the atmospheric air which is circulated through the channels formed between the metallic cases and the BCs can be seen in Figure 8. From Figure 7 and 8 it can be observed that solution Type 2 will allow to achieve a higher temperature of the hot air, while the opposite being solution Type 3. Comparing the hot air temperature at the same length we have values of ≈77°C for Type 1, ≈109°C for Type 2 and ≈80°C for Type 3. In accordance with the air temperature, when comparing the flue gases temperature at the same length we have values of ≈1432°C for Type 1, ≈1359°C for Type 2 and ≈1425°C for Type 3.

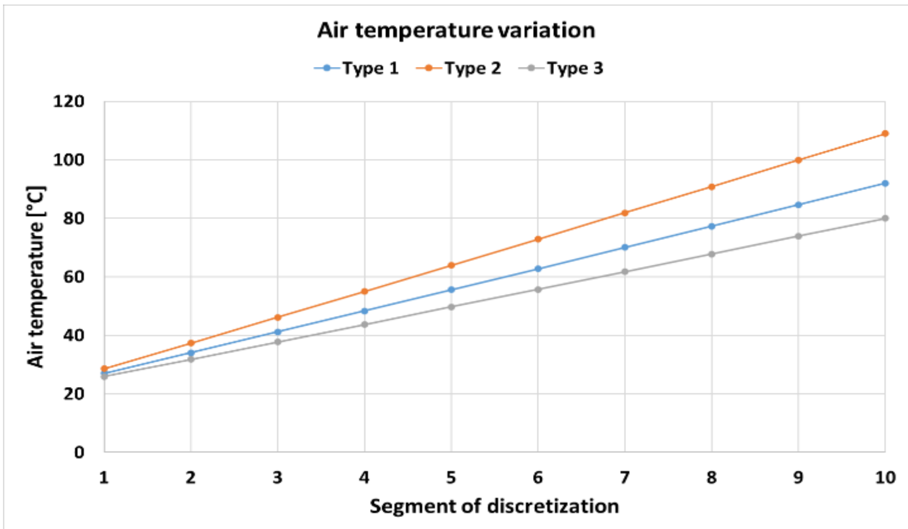

Figure. 8 Air temperature variation (T_{air})

From both figures one can assume that regardless of the length of Type 1 and Type 3 solutions, their construction will not allow a better heat transfer to the hot air than the Type 2 solution. So, if the purpose of the heating system is to achieve a higher hot air temperature for a convecto-radiator equipment, then a solution Type 2 would be recommended. If the purpose is to achieve a higher flue gases temperature for a radiation equipment, then a solution Type 3 would be more suitable.

Thus, it can be observed that depending on the purpose, the technical solution can be adapted as such with this type of calculation methodology. Monitoring the wall temperature of the metallic case will allow the user to optimize the design in order to obtain a low temperature, as is the case in this study (<150°C).

Although the wall temperatures for the casings was not a subject for this study, this parameter is correlated with the temperature of the hot air. Thus, we can make the correct presumption, as a simplifying hypothesis, that the wall temperatures for the casings where approximately similar with the hot air temperatures. Having temperatures below 150°C will allow the use of low-cost insulation material, like wood, and a safe operation of the BC.

The air velocity in the channel represents a parameter that helps determine the pressure losses. At the same time, it contributes to the correct sizing of the atmospheric air intake fan. Changing the flow section of the channel, the rib number and dimensions will affect the air velocity and, implicitly, the pressure losses.

The air velocity for all three solutions can be seen in Figure 9. From Figure 9 it can be observed that the values of the air velocities in the channels are not high. For Type 1 and Type 2 solutions, the air velocity appears to have a nearly identical linear decrease, without sudden changes, while for Type 3 solution the decrease evolves slightly.

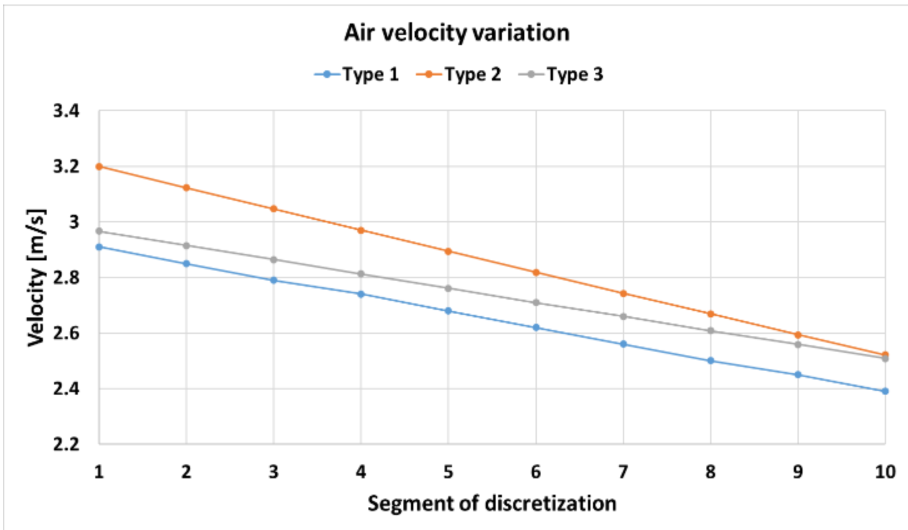

Figure. 9 Air velocity variation (v_{air})

One can assume that for solutions Type 1 and 3, the channels generate a higher pressure drop. When comparing the velocity values at the same length we have values of ≈2.5m/s for Type 1, ≈2.5m/s for Type 2 and ≈2.6m/s for Type 3. Thus, from an overview we can see that there are small differences between the values the three solutions, with a maximum difference of ≈0.2 m/s.

Another parameter of interest is the outside temperature of the metal casings. Figure 10 shows the wall temperature evolution, Tmet, of the BCs. In this figure we can see that all surface temperatures were under 250°C, while solution Type 3 had the lowest temperature, below 200°C. For temperatures below 450°C any ordinary steal can be used for constructing the BC walls.

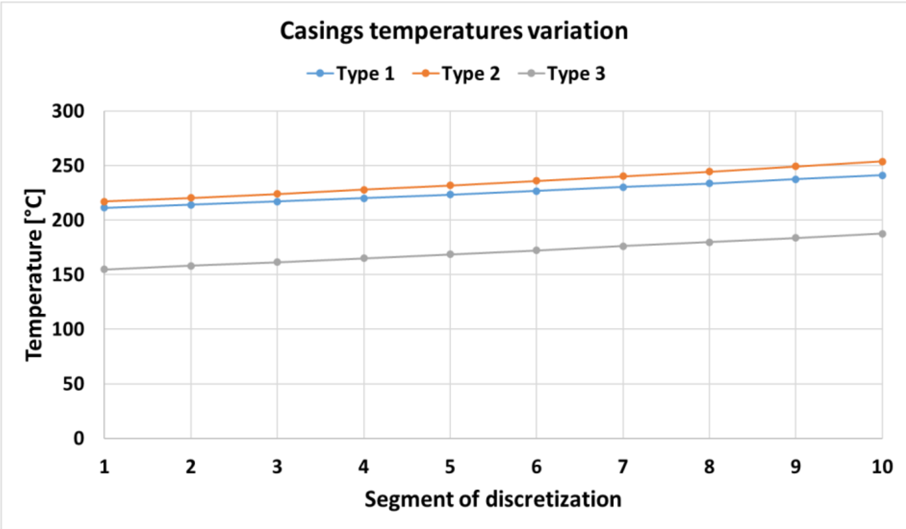

Figure. 10 Wall temperatures of the metal casings (T_{met})

Knowing the inner wall temperature of the BC will allow the user to determine the type of material required for the construction. Interior wall temperatures of the BCs were also determined (Figure 11).

When comparing the interior wall temperatures at the same length we have values of ≈1435°C for Type 1, ≈1364°C for Type 2 and ≈1429°C for Type 3, noticing a difference of ≈71°C between Type 1 and Type 2 solutions. As in the previous analysis, knowing the temperatures of the interior walls of the BC will allow a correct choice of the construction material, which will lead to a cost optimization. Be Correlating the modelling results from Figure 7 with the ones from Figure 8, we can see a normal interdependency between them which is due to the heat flux from the flue gases to the hot air.

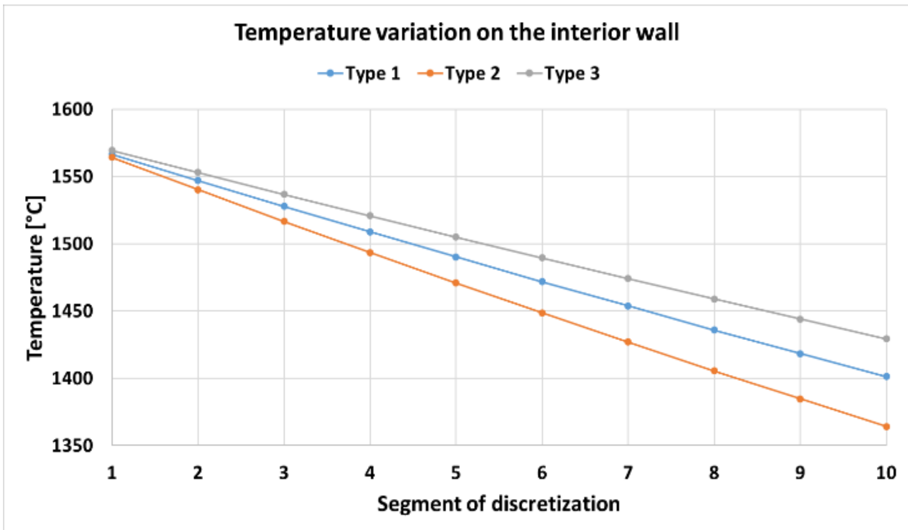

Figure. 11 Interior wall temperature variation (T_{wall})

The thermal power from the radiation-convection calculation (QT) resulted at each segment, for each solution, is presented in Figure 12 as percentage with regards to the thermal power of the burner (QBP), [(QT/ QBP)*100]. The total heat flux (QT) was resulted from the radiation and convection heat fluxes calculations. The thermal power of the burner (QBP) was as mentioned, 100kW for all solutions.

From this figure we can see that solution Type 2 achieved the highest thermal power from the three chosen solutions.

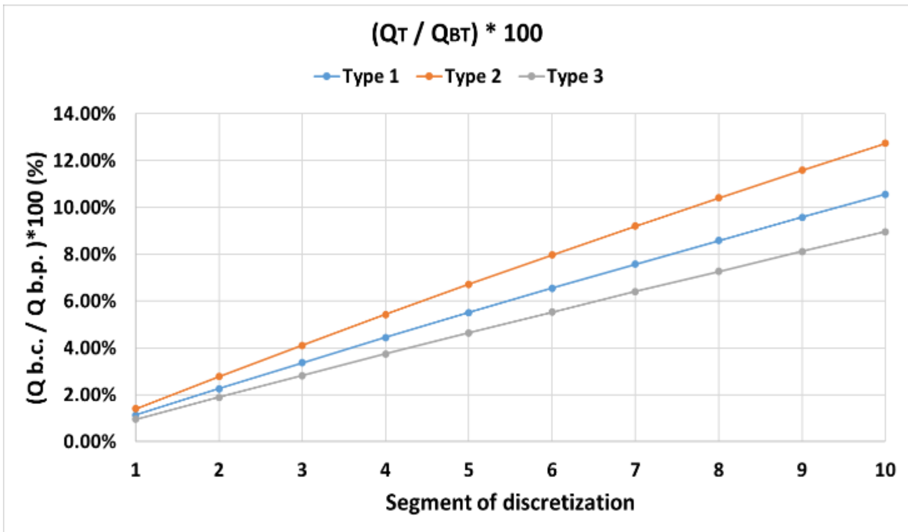

Figure. 12 Percentage of total heat flux, radiation and convection (Q_T), in regards to the thermal power of the burner (Q_{BP}); [(Q_T/ Q_{BP})*100]

5. Discussions

By using the segment discretization method, the purpose was to obtain information's on the variation of some defining parameters for the design and optimization of such equipment.

A parameter like the inner wall temperature is important because it defines the refractory quality of the material from which the furnace (BC) metallic structure it's made. Another important parameter to determine is the metallic case wall temperature. Controlling this temperature will allow the use of a cheap insulation, like mineral wool, and the safe operation of the equipment (regarding the outer surface temperature).

In the same time, knowing the wall temperature and the heat transfer factors on the hot air side (like the convective coefficient of heat transfer, the rib efficiency, the surface geometry) it is possible to optimize the shape and the dimensions of the ribs, having in mind that this represents a technological difficulty and a key factor of the investment. Thus, such approach and calculation methodology will allow to optimize and adapt the design of the equipment for the specific needs.

The present paper showed that this type of technical solution is feasible and can be applied successfully, in accordance with such a calculation methodology and with the intended purpose

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