THERMAL EFFICIENY AND HEAT FLUX OPTIMIZATION ANALYSIS OF A COPULA FURNACE

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***Abstract*-Furnaces are best reliable and operated with good thermal Efficiency and performance. Production and manufacturing is incomplete without foundry processes, hence, good melting operations become vital for casting. Copular furnace of 200kg capacity was designed and tested, parameters – insulation with bricks and clay; vortex cyclone effect blowing with motor of 5HP 2880 RPM ,good charging method , back pressure enhancement and maintaining steady supply of voltage are necessary for high thermal efficiency and performance where non defective products are guaranteed with the shortest resident time. The internal multiphase fluid flow analysis and ambient air flow condition are not left out as they affect heat transfer coefficients and thermal stress built up in the shell of the copular furnace due to temperature difference between inner surface and the outside the shell. Heat lost by emission of exhaust gases is minimized for improved thermal efficiency and performance.**

Index Terms: Heat Flux optimization, thermal Efficiency, Vortex cyclone effect, reduced resident time ,copular furnace

1.Introduction

Hot forming operation and metal melting casting are manufacturing operations on which every other engineering works are possible. Among the numerous foundry operations, metal melting forms a synequano in which other operations depends. Furnaces serve as the bed rock of foundry operations. They are designed on capacity and materials base; but the mode and orientation of firing are different. Tilting furnace, Rotary furnace, Electrical are furnace, copular furnace and blast furnace are designed and developed for different purposes. Heating or firing mode can be charging method with charcoal and coal (coke), petroleum oils – gas, diesel, kerosene etc. But, heat production or the efficiency of the firing is dependent on the fuel type, firing method and orientation and the orientation & configuration of the furnace. Copula furnace is a reactor design for melting of cast iron, the firing or charging is different from other forms of furnaces that are fired using liquid fossil fuels via burners and good nozzles. The problem in this is the flame instability that will affect the thermal efficiency and performance of the furnace. Thus, improving the residence time of the metal in the furnace. Copular furnaces are charged by burning of charcoal or wood to ignite the coke in the lower chamber and followed it with the blast of air which has a cyclone effect to eliminate all the charcoals, particles of coke impurities via the exhaust air. There is a considerable heat lost in this process. Copula furnace is the heart of casting process as described in fig1.

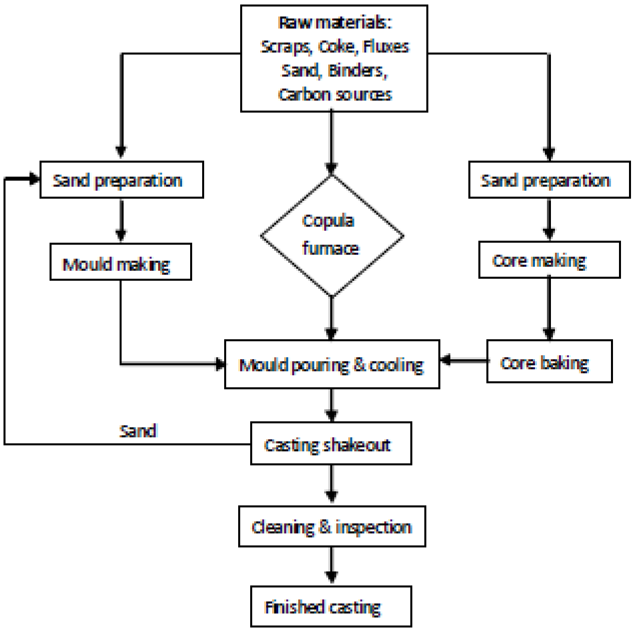


Fig 1 . Copula furnace as heart of casting process

2. Description

Cupola furnace is used for melting scraps of metals or pig iron for production of various cast irons. The production of nodular and malleable cast iron is possible, available in good varying sizes. The main considerations in selection and design of cupolas are melting capacity, diameter of shell without lining or with lining, spark arrester. The construction of a conventional cupola consists of a vertical steel shell which is lined with refractory bricks. The charge is introduced into the furnace body by means of an opening approximately half way up the vertical shaft. The charge consists of alternate layers of the metal to be melted, coke fuel and limestone flux. The fuel is burnt in air which is introduced through tuyeres positioned above the hearth. The hot gases generated in the lower part of the shaft ascend and preheat the descending charge. The charge, consisting of metal, alloying ingredients, limestone, and coal coke for fuel and carbonization (8-16% of the metal charge), is fed in alternating layers through an opening in the cylinder. Air enters the bottom through tuyeres extending a short distance into the interior of the cylinder. The air inflow often contains enhanced oxygen levels. Coke is consumed. The hot exhaust gases rise up through the charge, preheating it. This increases the energy efficiency of the furnace. The charge drops and is melted. Although air is fed into the furnace, the environment is a reducing one. Burning of coke under reducing conditions raises the carbon content of the metal charge to the casting specifications. As the material is consumed, additional charges can be added to the furnace. A continuous flow of iron emerges from the bottom of the furnace depending on the size of the furnace; the flow rate can be as high as 100 tones per hour. At the metal melts it is refined to some extent, which removes contaminants. This makes this process more suitable than electric furnaces for dirty charges. A hole higher than the tap allows slag to be drawn off. The exhaust gases emerge from the top of the cupola. Emission control technology is used to treat the emissions to meet environmental standards. Hinged doors at the bottom allow the furnace to be emptied when not in use.

Fig2 . pictoral view of a copula furnance in use SEDI ,Enugu

3.Heat Energy Source

The cupola produces cast iron by melting scraps and alloys using the energy generated from the oxidation (combustion) of coke, a coal refined. But the coke is lighted by dried wood that lighted and fired by the blast air to light up the coke for heating. The blast air has vortex ability as the air is sent tangential to the air box to eliminate all burnt wood charcoal, particles, sands and gaseous emission via the exhaust hot air.

4.Type of Molten Metal

Cupola furnace is employed for melting scrap metals or (over 90 %) of the pig iron used in the production of iron castings. Gray Cast iron, nodular cast iron, some malleable iron castings and some copper base alloys are metallic materials can be produced by

Cupola Furnace. Molten metal is denser than the slag hence the former tapping hole is at the bottom of the furnace while the latter is at the upper most as it flows on the molten metal.

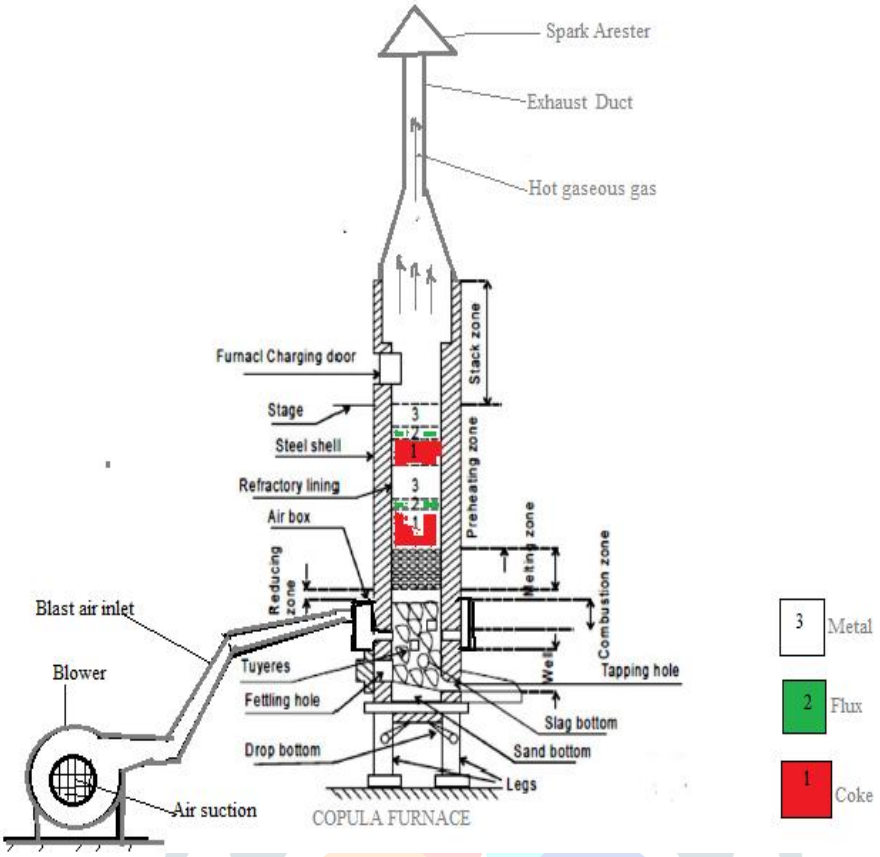


Fig.3 Sectioning of a copula furnace showing the components, stacks arrangement metal scraps and coke and air blast parts.

5. Scope

This work covers the heat flux, thermal Efficiency, performance optimization analysis of a copular furnace. Vortex cyclone analysis of the blasting air from a 5HP 2880 RPM blower , and the effect on back pressure increase and its effect on heat flux increase in the furnace. Internal turbulent flow of the multiphase gas stream as well as thermal stress owning to temperature difference between inner parts and the ambient condition.

6. Statement Of Problem

There is considerable heat lost in copula furnaces during melting operations in the furnaces. This leads to loss of man-hour due to long resident time, materials like coke, electrical energy and pour product output. The cost implication of these is enormous and the need to optimize the operating parameter to have a high efficient copula furnace.

7. Aims And Objectives

This paper work is researched on the following grounds

(1) To analyze the heat flux kinetics of a copular furnace
(2) Maximize thermal efficiency
(3) Optimize firing & particles of impurities and removal through vortex cyclone effect of the blasting air
(4) Back pressure increase through shape optimization to reduce heat lost via exhaust air.

Copular furnaces are designed and operated without heat conservation and a considerable amount of heat is lost via exhaust. Thus affecting the material resident time.

8. Significance

The essence of this work is to visualize ways by which the heat flux and thermal efficiency of a copular furnace can be optimized via a knowledge based software – SOLID works and ANSYS. This will help as a guild to go a long way to helping in future designs of copular furnaces

9. Materials

Copular furnace is designed and developed with locally sourced materials – Mild steel material for its machinability, clay bricks and clay soil for its low thermal conductivity (k) and diffusivity (α) . the bricks and clay are the insulating median used in the lining of the wall of the furnace.

10. Thermal Analysis.

Charging of copular furnace begins with burning of the wood charcoal with coke. It is done to light up the coke. This is aided with air blasting from the high speed which are sent tangential to the charging chamber. Heat the heat content value of wood charcoal and coke.

$$Coke_s + O_{2\,(g)} = CO_{2(g)} + H_2O_{(g)} + Heat\,Value(energy) \qquad (1)$$

$$Wood\ charcoal + O_{2\,(g)} = CO_{2(g)} + H_2O_{(g)} + Heat\ value(Energy) \qquad (2)$$

Plentiful supply of air aids Complete combustion, hence it is free of CO (Carbon II Oxide)

By analysis the calorific values of coke and wood charcoal become necessary in this work.

If the heat generated bye the mixture of wood and coke

$$Q = m_i(Vcoke + (Vwood),\ i = 1\,\&\,2 \qquad (3)$$

Where

m_1=mass of coke

m_2=mass of wood

$$Qi = (Vcoke + Cvwood) \qquad - \qquad (4)$$

Q_i = heat generated from a unit mass of coke and charcoal

(Vcoke = colorific value of a unit mass of coke

Cwood = Calorific value of a unit mass of wood charcoal

Heat required to melt Mkg of cast iron material. From fourier of conduction

$$Q_{\ melt} = MC\Delta\emptyset \qquad (5)$$

$\Delta\emptyset$ = Temperature difference between the feeding or charging gate and the molten metal pouring temperature

C = Specific heat capacity of the cast iron material

M = Mass of Cast Iron material to be melted.

It should be noted that the whole melting process covers the temp of the feeds (cast iron) into the furnace and the pouring temp. this governs the fluidity of the molten metal and gaseous escape from the molten metal.

11.The Heat Lost

Heat lost can be calculated as heat absorbed by the Insulators, heat lost by the exhaust gases, infiltration and heat required to melt the metal and raised the molten metal to pouring temperature.

Heat Lost To The Surrounding

The wall of the copular furnace is a double wall comprising the bricks lining and the mild steel shell . This helps in the insulation works of the furnace, as in fig.3, the bricks lining is held in position by spatial arrangement of mild steel studs in the internal wall of the shell.

From fourier law of heat conduction

$$Q = KA\frac{dT}{dx} \qquad (6)$$

For a cylindrical material, the heat lost via the walls is calculated

$$A = \pi DL \qquad (7)$$

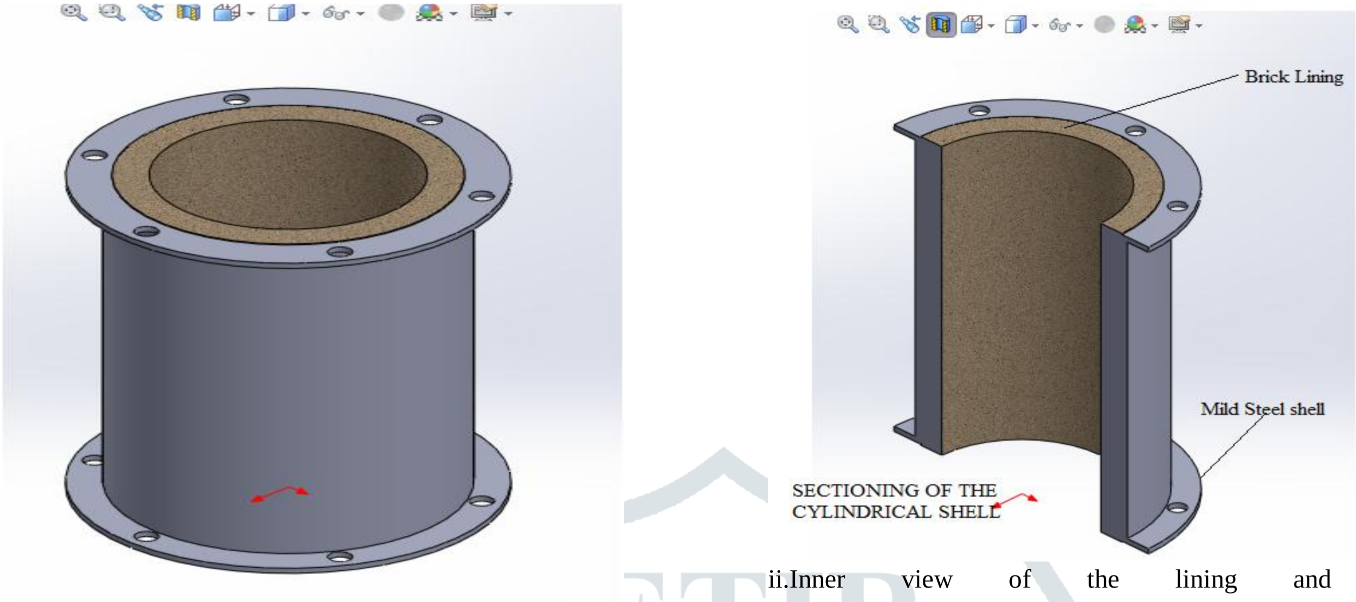
Where

A = internal surface area of the furnace

D = Internal Diameter of the furnace

L = length of the Cylinder. This covers the total length of the tapping drum, charging drum and feeding drum; since they are the same diameters.

Consider a cross section of the copular furnace



ii.Inner view of the lining and shell

i. cylindrical Shell of the furnace

Fig. 3cross section of the furnace

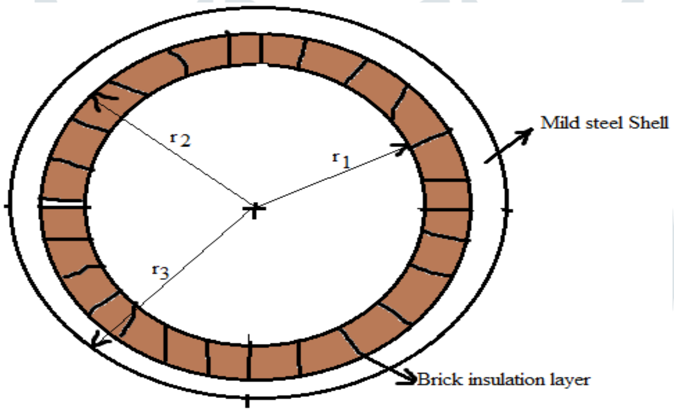


Fig.4. Cross section of the copula furnace

The total heat lost via the doubled walled Cylinder of the copular furnace is determined as;

$$Q_t = \frac{2\pi L(T_i - T_0)}{\frac{1}{h_i r_1} + \frac{\mathrm{In}(r_2/r_1)}{k_{st}} + \frac{\mathrm{In}(r_3/r_2)}{k_{br}} + \frac{1}{h_0 r_3}} \qquad (8)$$

Where

$Q_t = total\ heat\ lost\ through\ the\ cylindrical\ shell\ and\ the\ brick\ linning$(KW)

$T_i\ and T_o = inner\ temperature\ \ and\ outside\ temperature\ of\ the\ ambient\ condition\ respectively$(°C)

$r_3 - r_2 = thickness\ of\ the\ steel\ shell$(m)

$r_2 - r_1 = thickness\ of\ brickn\ lining$(m)

$L = Length\ of\ the\ shell(m)$

$k_{st} = Thermal\ conductivity\ of\ the\ mild\ steel\ material(kw/m$°C)

$k_{br} = Thermal\ conductivity\ of\ the\ bricks\ material(kw/m$°C)

$h_0 = coefficient\ convective\ heat\ transfer\ of\ the\ ambient(kw/m$°C)

$h_i = coefficient\ convective\ heat\ transfer\ of\ the\ ambient(kw/m$°C)

$$Qt = UA_T\Delta T \qquad (9)$$

$\Delta T = temperature\ difference$(°C)

U = over all thermal conductivities

$A_T = A_{TB} + A_{TS}$ (10)

Where

A_T = Total Surface Areas of the clan bricks and the mild steel cylinders.

A_{TB} = Total surface Area of the clay bricks.

A_{TS} = Total surface Area of the mild steel cylinder

Heat lost due to infiltration can be assumed as (5%) of the heat generated. Heat lost to the exhaust is the 25% of the total heat generated.

Therefore, the total heat generated can be calculated as

$Qgen = Qmelt + Qin + Qexh$ (11)

$Qgen = Qmelt + Qlost\ wall + 5\%\ Qgen + 25\%\ Qgen$ (12)

Where,

$Qgen = heat\ generated$

$Qmelt = heat\ required\ to\ melt\ the\ metal\ to\ molten$ state

$Qin = heat$ lost from infiltration

$Qexh = heat\ lost\ by\ exhaust\ gases$

The heat lost in the copular furnace is greater through hot exhaust gases and it control will be discussed in later sections .Thermal efficiency is a function of the resident time. This is because resident time will reveal factors like good insulation, good charging and firing and exhaust control. The lower the resident time of the cast iron in the furnace the high the thermal efficiency of the copula furnace .

$\eta_{th} = \frac{Q_{melt}}{Qgen}\ x\ 100\%$ (13)

$\%\ heat\ lost = \left[1 - \frac{Q_{melt}}{Q_{gen}}\right]\%$ (12)

12. FLOW ANALYSIS

For convection in turbulent flow in internal insulated circular shell (internal flow), it is calculated by [Erek 2005]:

$Uu_D = \frac{(f/2)(Re-1000)Pr}{1+12.7(f/2)^{1/2}(Pr^{2/3}-1)}$ (15)

$f = (1.58InRe - 3.28)^{-2}$ (16)

Air Heat Transfer Coefficient

To determine air heat transfer coefficient outside the shell, the following definition is used Incropera,[2002]

$h_c = \frac{Nu_D K_a}{D_o}$ (17)

Kf is heat conductivity of the hot air stream (W/m.°C), ID is inner diameter of the pipe (m) and Re is Reynold’s number. For furnace internal flow with a temperature of 1500 °C and a pressure of 25E7 Pa,. Prandtl number (Pr) is the ratio of momentum and thermal diffusivities, α [Incropera, [2002]. hc is heat transfer coefficient (W/m2 .°C), ka is heat conductivity of air (26.3e-3 W/m.°C), D_o is outer diameter of the shell (m), Nu_D is Nusselt number, it is the dimensionless temperature gradient at the surface.For air free convection around a long cylinder, it is given by [Incropera, 2002]:

$Nu_D = \left\{0.6 + \frac{0.387{Ra_D}^{1/6}}{\left[1+(0.559/Pr)^{9/16}\right]^{8/27}}\right\}$ (18)

where Ra_D is Rayleigh Number, defined in equation (10) [Cengel, 2003], while *Pr* is Prandtl number,which is the ratio of momentum and thermal diffusivities,

$Ra_D = Gr_D Pr$ (19)

where *GrD* is Grashof Number, which is defined as [Cengel, 2003]:

$Gr_D = \frac{g\beta(T_S - T_\infty){D_i}^3}{v^2}$ (20)

Where *g* is acceleration of gravity (*m/s2*), *β* is coefficient of volumetric thermal expansion (K^{-1}), *Ts* is source temperature (°*C*), *T*∞ is Stream temperature (°*C*), D_i is inner diameter (*m*) and *v* is kinematic viscosity (m^2/s).

13. THERMAL STRESS

The stress is developed in the column shell of the copula furnace due to temperature gradient which results from heat flux. In order to determine the maximum stress, the system can be modeled using transient thermal analysis, whereby structural analyses are conducted over multiple periods of time to determine the maximum stress value.The calculated stresses include von-Mises and maximum shear stress. Von-Mises failure criterion is defined as [Hosford, 2005]:

$(\delta_1 - \delta_2)^2 + (\delta_2 - \delta_3)^2 + (\delta_1 - \delta_3)^2 \le 2{\delta_y}^2$ (21)

Where

$\delta_1, \delta_2\ and\ \delta_3$ are the principal stresses, and δ_y is the yield stress for the ductile material.

Thermal stress $\delta_{thermal}$ is generally expressed in the form, NEA, [1998]

$\delta_{thermal} = C.E\alpha\Delta T$ (22)

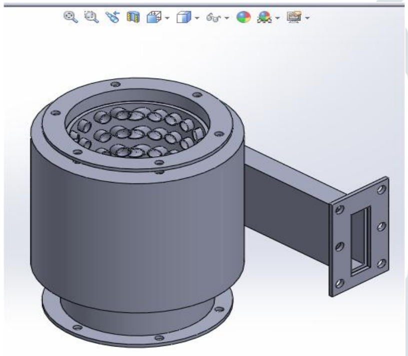
The factors that affect thermal stress are *E* which is Modulus of Elasticity (*MPa*), α which is coefficient of thermal expansion ($°C^{-1}$), ΔT which is temperature gradient (°*C*) and *c* which is a constant of proportionality. The constant depends on the condition of mechanical constraint, temperature distribution, and Poisson's ratio. Thermal stress analysis is based on transient analysis rather than steady-state, because the latter usually underestimates its value. Boyce, [2004]. Therefore, the first step is to define a transient thermal analysis, which is used to conduct the structural analysis. It is worth noting that it is not known in advance when the maximum stress occurs, therefore it is necessary to investigate the whole transient period to find the maximum stress value. The value of the maximum stress is used to predict the furnace column shell model life based on fatigue analysis. Thermal stress has more effect on service life than mechanical stress. The effect can be as much as 2.5 percent lower cycles [Oberg].

14. Optimization

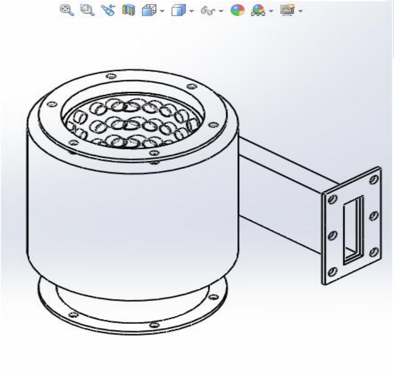
This work is optimized from conceptual designs having seen as an existing one in working condition. The optimization will help to achieve an improved design that will have the shortest resident time for Cast iron melting and reduce heat lost via exhaust gases:

a. Improve Vortex Cyclone Effect

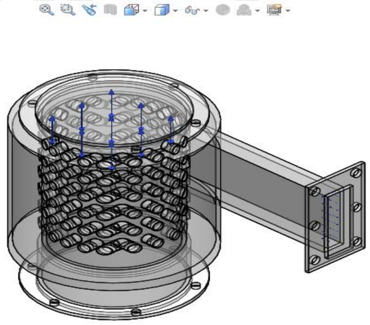
The charging orientation and configuration of the copular furnace necessitates a means where Coke particles, Sands, Charcoal and gases from coatings of the materials fed into it. Hence the whole copular furnace has a design shape configuration that can be idealized and once actualized as a cyclone. The orientation of the inflow of the charging blasting air determines the cyclone effect that can eliminate the dirts, sands, impurities in the molten system. Hence, various speed and orientation are investigated to see the one that will give more whirling or cyclone effect. Using solid works 2013 the air box flow simulation was conducted to visualize the vortex effect.



i.Solid form of the copula furnace air box

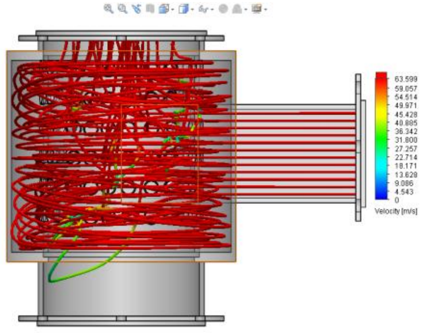


ii.Wire frame of the copula furnace air box

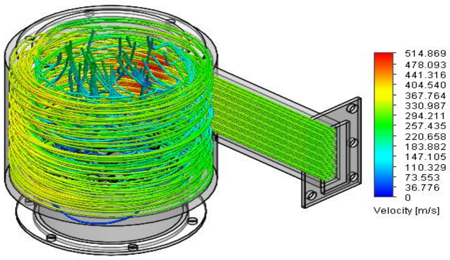


iii.Glassy representation of the copula furnace air box

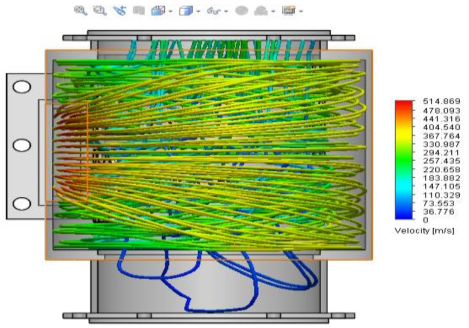
fig.5. the air box of the copula furnace for air blasting



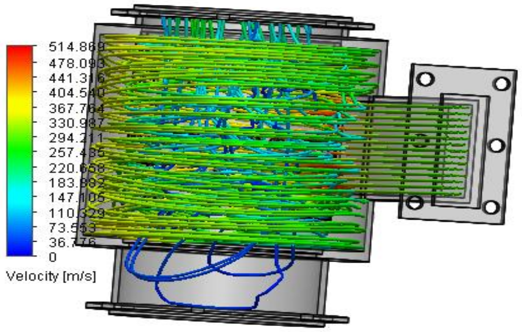
a. High Flow vortex

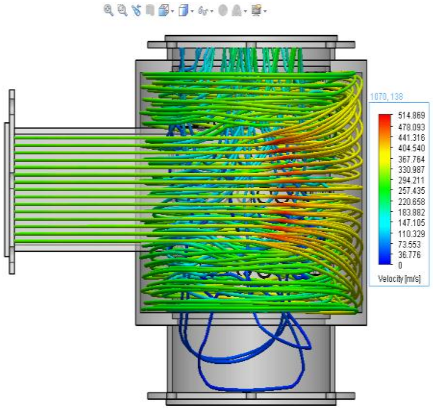


b.flow votex



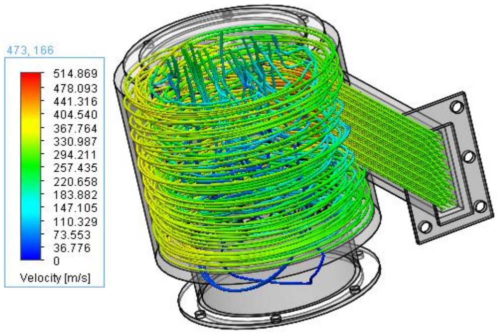
c.back view of the flow votex





c.side view of flow vortex

d.view of the vortex



e.flow vortex

Fig.6. flow simulation of the vortex cyclone effect in the air box with the inner cylinder as the vortex finder.

The blast air duct irrespective of the geometrical orientation must be tangential to the air box. This therefore help in the whirling of the blast air along in the inner wall of the air box.T0 aid effective combustion ,and blow out particles of sand, charcoal and gases out the furnace.

b. Increase of Back Pressure

Back pressure favours flow of the hot air stream from the furnace, to reduce the flow speed, the back pressure should be increased which reduce the speed of flow of the hot stream of gases and retain more heat within the furnace to minimize heat lost through exit of gases and hot air at the chimney. The back pressure is increased by adopting a swollen neck section immediately the charging door.This is by adopting a CD channel pattern for pressure and speed of flow variation.

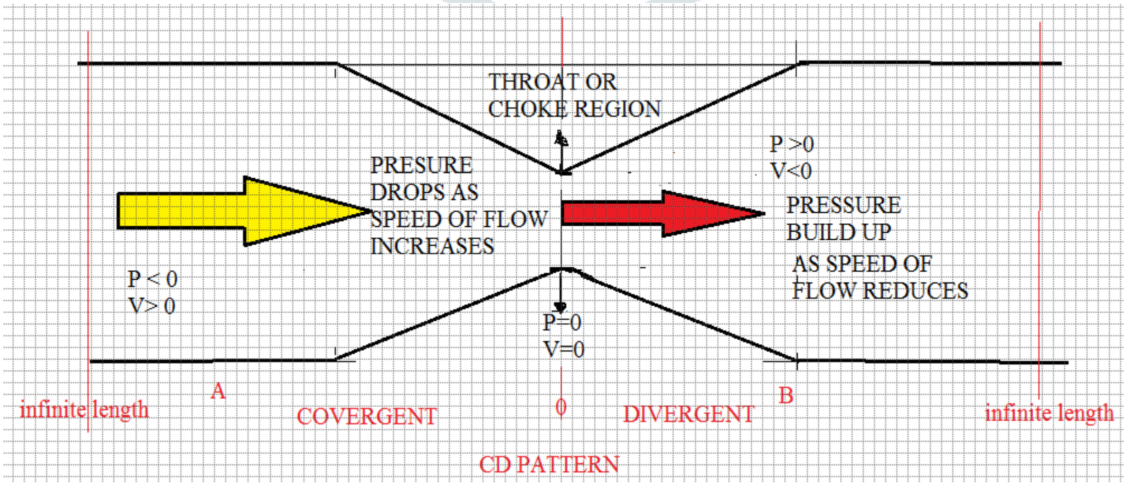
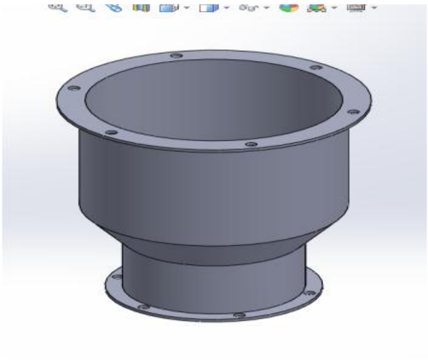
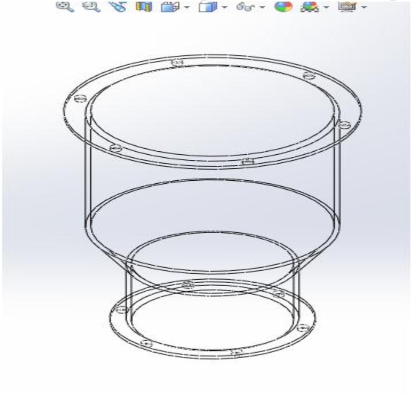


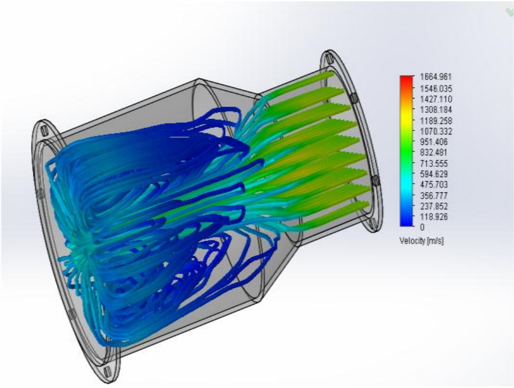
Fig.7, The CD channel pattern



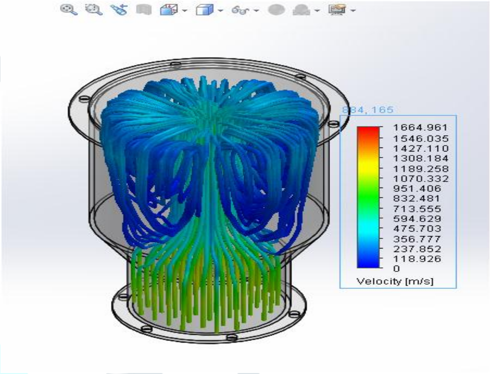
i.solid form of the pressure increase part



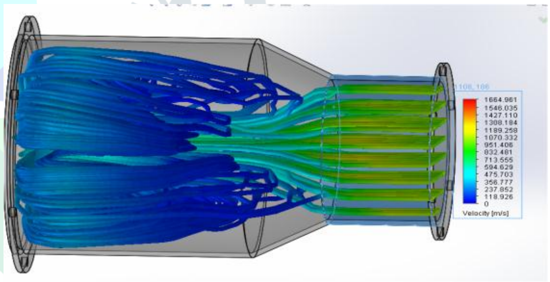
ii. solid form of the pressure increase part



iii.slant view of flow simulation



iii.vertical view flow of simulation



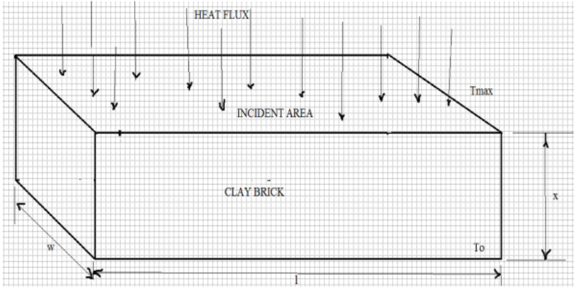
iv.horizontal view of flow simulation

fig.8.pressure increase and speed reduction in a divergent channel

The divergent or B side is suggested to be adopted in design immediately the air box for air blast region.

c.Use Of Clay Bricks

The clay bricks has low thermal conductivity hence it availability could be used as advantage to produce clay bricks for the lining of the copula furnace. Parameters like bricks hardness and ,thickness should not be undermined.



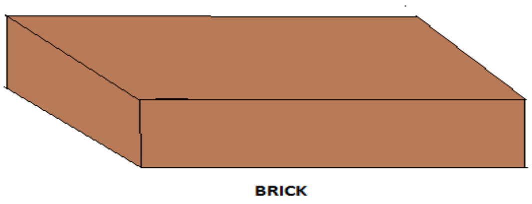


Fig9. A representation of Brick for lining the metal shell of the copula furnace

The differential heat balance for bricks insulation considering a brick using conduction and convection

$$G_b C_b \frac{dT_b(x)}{dx} = hA_b\left(T_g - T_b\right) \qquad (23)$$

$G_b(x) = superficial\ gas\ mass\ flux$

$C_b = heat\ capacity\ of\ brick$

$T_{b(x)} = temperature\ differential\ across\ the\ thickness\ (x)\ of\ the\ brick$
$dx = thickness\ differential (x)$
$A_b = surface\ area\ of\ the\ bricks$
$T_g\ \&\ T_b = temperature\ of\ hot\ gas\ and\ brick\ respectively$
$h = convective\ heat\ transfer\ coefficient$

CONCLUSION

The heat flux and thermal efficiency of the copular furnace is optimized through insulation enhancement, increase in back pressure which reduces the velocity of flow of hot multi-phase air stream and optimized vortex effect of the blast air from the blower. Ensuring steady supply of voltage to avoid pulsating of the blower is vital to avoid shocks and resonating effect of the pulsating in the supply of the blasting air necessary for most of these factors to be functional. This therefore, reduces resident time and minimizes cost of production, energy, and maximize good quality of products that are free of defects.

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