

Thermal Design of an Oil Fired Crucible Furnace using CFD Technique

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ABSTRACT

Thermal design of a furnace could be complex and time consuming as it requires iterative calculations to arrive at expected operating temperature values of the various parts or segments of the furnace. A more accurate and time saving approach to furnace thermal design is the Computational Fluid Dynamics (CFD) technique. Hence, this study, a thermal design of an oil fired crucible furnace is carried out using the CFD application in Solid Works flow simulation software. A CFD domain was set up, and simulation parameters such as mesh analysis, material settings and boundary conditions were applied. Result of the CFD reveal that temperatures of 1131.1 K, 776.8 K, 313.2 K, and 301.1 K will exist at the crucible pot, refractory wall, casing and cover of the crucible furnace respectively. The study also indicates that the average temperature of the refractory wall would be able to withstand the thermal stresses induced by the temperature. The temperatures of the casing and cover suggest that deformation arising from furnace operation will be quite negligible, and that no hazard is posed to both the foundry operator and the diesel fuel since the maximum external temperature of 313.2 K is less than the flash point of diesel fuel which ranges from 325 K to 369 K. The study recommends that the furnace would be suitable for melting aluminum since the temperature of the crucible pot is higher than the melting point of aluminum.

Key Words: Heat flux, Temperature, Simulation, Computational, Domain.

INTRODUCTION

A furnace is a lagged enclosure designed primarily for heating of metals in order to achieve a metallurgical change. This change could either be to refine the microstructure of the metal as in the case of a heat treatment furnace, or it could be to attain the pouring temperature of the metal as in the case of melting. In a study on the Design and Development of a Gas Fired Reverberatory Furnace: In View of Huge Gas Reserves in Nigeria, ^[1] noted that furnace design is a complex process, and the design can be optimized based on multiple factors. One of such multiple factors is the thermal factor which comprises of: the surface heat flux, thermal conductivity of solid, and heat transfer rate. In carrying out thermal designs, Computational Fluid

Dynamics (CFD) has become a helpful tool for heat transfer studies, this approach among many other benefits enables the designer to have a better understanding of the work being designed while saving the cost and time involved in running tests aimed at generating performance data prior to the validation and production stages. Researches such as Modeling and Event Based Simulation of an Earthmoving Digger Using Solid Works Premium 2014 carried out by ^[2] shows the effectiveness of CAD models and simulation in engineering design process. Therefore, this study aims at carrying out a thermal design of an oil fired crucible furnace using the CFD feature available in Solid Works Flow Simulation software. The objective of CFD study is to simulate prevailing physical and

thermodynamic conditions in the modelled furnace and interpret its performance.

Furnace Description

Component Description and Material Selection

The crucible furnace is made up nine main components viz: The crucible casing, crucible refractory layer, crucible pot, fuel atomizer, a fuel delivery hose, an air delivery hose, a fuel tank, an electric motor, and an air compressor.

Crucible Casing: This is the outermost part of the crucible furnace. It is made up of a 3660mm by 1525mm by 2.5mm BS 1449-S1.2 (1991) Hot rolled mild steel sheets. Attached to it is a top cover which prevents heat loss by convection. It is also designed to have a 200mm vent at the upper end for the escape of flue gases and also another 200mm opening at the lower end for introducing the atomized fuel needed for combustion. This lower end leads to the furnace combustion chamber.

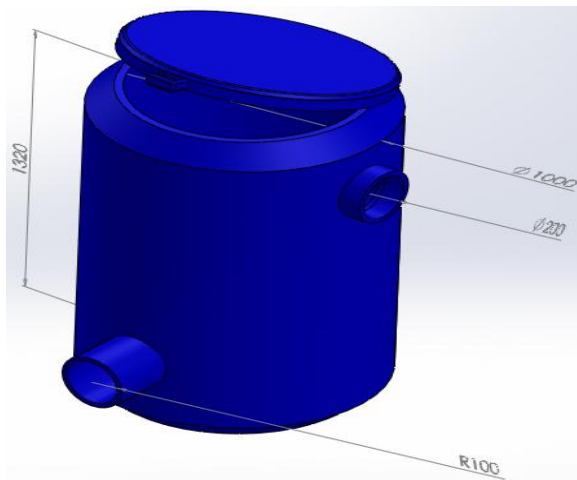


Figure1: A 3D model of the Crucible Furnace casing.

Crucible Refractory Brick wall: This separates the crucible pot from the crucible casing. It functions to retain heat and prevents heat loss from the furnace to the casing via conduction. It also helps maintain high furnace temperature which enables complete fuel combustion. The refractory wall is a composite made up of Portland cement, asbestos and clay in a ratio of 2:1:1. Just like in the crucible casing, there is a

vent of 200mm in diameter located at both the top side and bottom side ends of the wall. The bottom vent leads to the combustion chamber where the atomized fuel is ignited. A groove of 50mm in width is created running along the inner part of the wall from the combustion chamber to the upper vent. This provides an escape route for the flue gases.

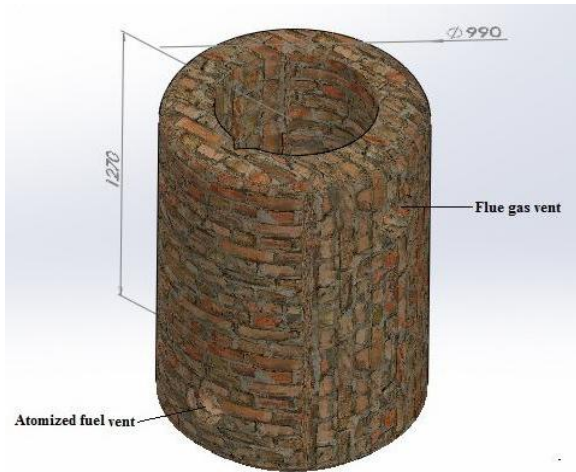


Figure 2: A 3D model of the crucible furnace refractory wall.

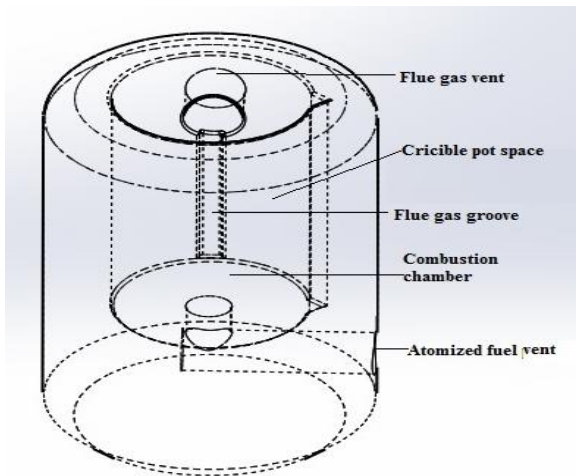


Figure 3: Internal structure of the furnace refractory wall.

Crucible Furnace Pot: The crucible pot contains the Aluminum to be melted. It is made up of a copper alloy material because of the high thermal conductivity of copper, and its melting temperature being higher than that of aluminum. A spout is incorporated to aid pouring of the molten aluminum.

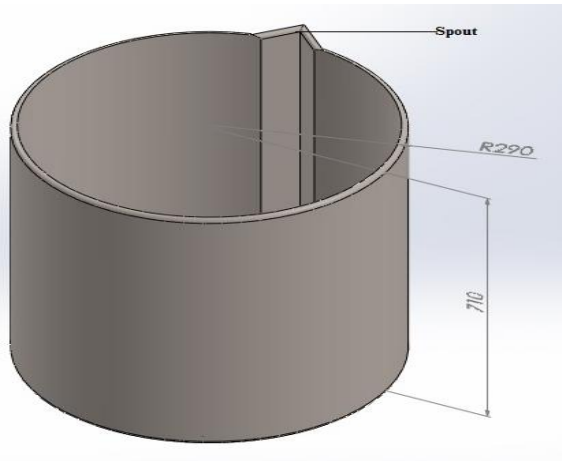


Figure 4: A 3D model of the Crucible pot.

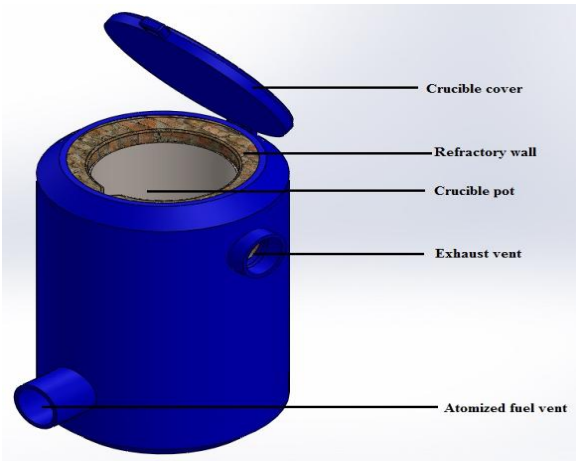


Figure 6: A 3D model of the crucible furnace.

Fuel Atomizer: The fuel atomizer directs the spray into the combustion chamber while breaking up the diesel oil into very fine particles thereby enhancing a fine spray. A return-flow atomizer was used to achieve the needed fine spray. It works by mixing the air and fuel which are introduced separately into it. The air and fuel are mixed in the whirling chamber so that a uniform swirl of air and fuel converge at the orifice plate causing a very fine spray to be achieved.

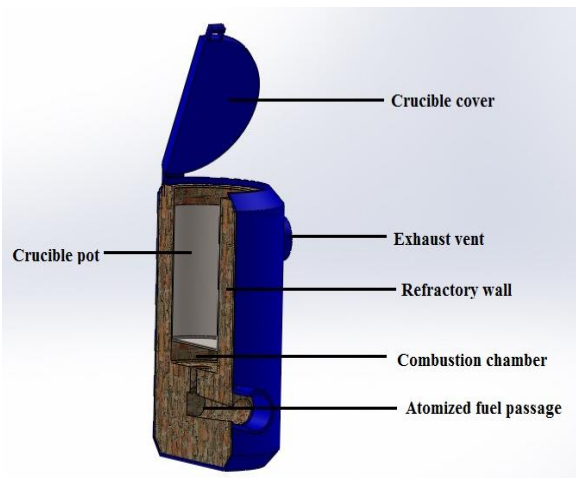


Figure 7: A sectioned right plane of the crucible furnace.

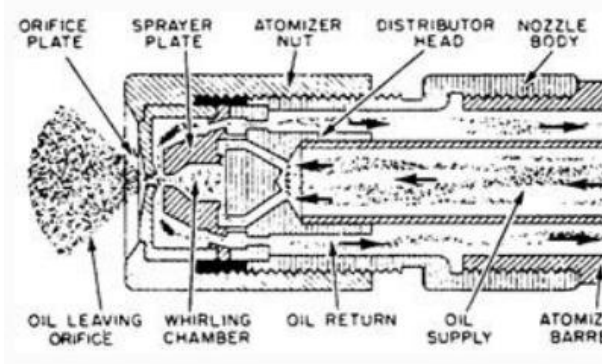


Figure 5a: Internal structure a return-flow atomizer.

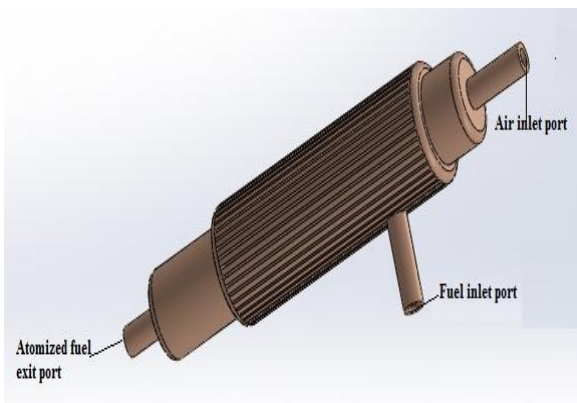


Figure 5b: A 3D model of a return-flow atomizer.

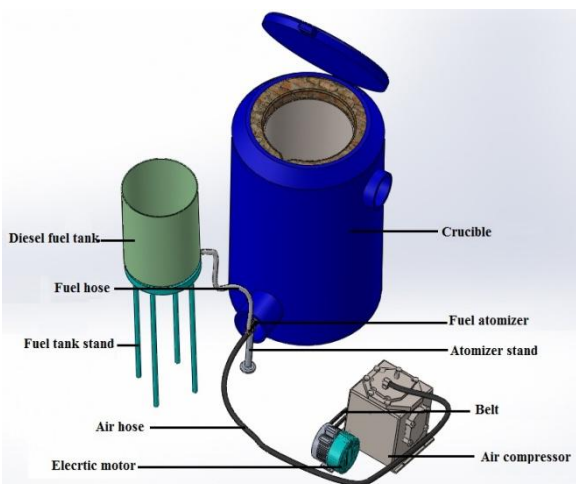


Figure 8: An assembly model of the crucible furnace.

Air and Fuel Delivery Hoses: These functions to deliver air from the air compressor to the fuel atomizer and from the fuel tank to the fuel atomizer. For the air and fuel delivery lines, a ¼” rubber hose was used.

Fuel Tank: This component is used to store the diesel fuel used in the combustion process for the generation of the needed heat for melting the aluminum scraps. It is made up and aluminum because aluminum is resistant to corrosion and favours long storage of diesel fuel.

Electric Motor: It serves as the prime mover of the air compressor. It converts the electrical energy which is its source to mechanical energy used to drive the air compressor.

Air Compressor: It utilizes the mechanical energy from the electric motor to suck in successive volumes of atmospheric air, compresses the sucked-in air and then causes the compressed air to exit at very high pressure.

This high pressured air impacts on the diesel oil in the fuel atomizer and with the aid of the return-flow atomizer, a fine spray is obtained.

METHODOLOGY

In carrying out the CFD study, it is assumed that the heat transfer coefficient of the refractory material is $5 \text{ W/m}^2\text{K}$, while that of the crucible casing is $27 \text{ W/m}^2\text{K}$. This assumption is based on their thermal conductive abilities. The furnace initial temperature was set to be at thermal equilibrium with the environment at 293.2K . Considering the combustion temperature of 602 K for diesel fuel, [3] and also the possible temperature build up in the combustion chamber, the combustion chamber maximum temperature was set at 855.2 K .

Size of Computational Domain: The computational domain specifies the region under investigation. It is within this domain that the computer will carry out all CFD commands/operations. Details on the size of computational domain is given in Table 1.

Table 1: Size of Computational Domain

X min	0.098 m
X max	1.170 m
Y min	0.136 m
Y max	1.713 m
Z min	1.136 m
Z max	2.346 m

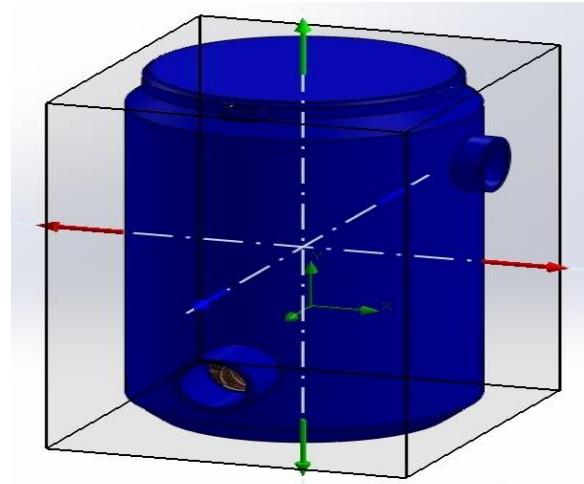


Figure 9: Computational domain of the crucible furnace.

Simulation Parameters: These parameters include: Analysis mesh, Material settings, and boundary conditions. The analysis mesh instructs the program on the number of discrete elements the model should be broken into. The accuracy of the results is always enhanced by higher mesh values. The material settings input the properties of the materials within the computational domain, while the boundary conditions specify the operating conditions.

Analysis Mesh

Total Cell count: 164801

Fluid Cells: 0

Solid Cells: 104434

Partial Cells: 60367

Trimmed Cells: 0

Material Settings

Table 2: Refractory material

Parameter	Value
Density	9630 kg/m^3
Specific heat	$1.55 \text{ J/(kg}^*\text{K)}$
Conductivity type	Isotropic
Thermal conductivity	$0.2150 \text{ W/(m}^*\text{K)}$
Electrical conductivity	Insulator
Radiation properties	No
Melting temperature	No

Table 3: Steel (Mild)

Parameter	Value
Density	7870.00 kg/m^3
Specific heat	$472.0 \text{ J/(kg}^*\text{K)}$
Conductivity type	Isotropic
Thermal conductivity	$51.9000 \text{ W/(m}^*\text{K)}$
Electrical conductivity	Conductor
Resistivity	$1.7400\text{e-}007 \text{ Ohm}^*\text{m}$
Radiation properties	No
Melting temperature	Yes
Temperature	1673.15 K

Table 4: Copper

Parameter	Value
	8960.00 kg/m ³
Specific heat	385 J/(kg*K)
Conductivity type	Isotropic
Thermal conductivity	400 W/(m*K)
Electrical conductivity	Conductor
Resistivity	1.7200e-008 Ohm*m
Radiation properties	No
Melting temperature	Yes
Temperature	1673.15 K

Boundary conditions

Table 5: Refractory Wall

Type	Inner Wall
Coordinate system	Global coordinate system
Reference axis	X
Heat transfer coefficient	5.000 W/m ² /K
External fluid temperature	855.20 K

Table 6: Crucible pot Wall

Type	Outer Wall
Coordinate system	Global coordinate system
Reference axis	X
Heat transfer coefficient	5.000 W/m ² /K
External fluid temperature	855.20 K

Table 7: Crucible outer Wall

Type	Outer Wall
Coordinate system	Global coordinate system
Reference axis	X
Heat transfer coefficient	27.810 W/m ² /K
External fluid temperature	298.20 K

Table 8: Crucible cover

Type	Outer Wall
Coordinate system	Global coordinate system
Reference axis	X
Heat transfer coefficient	27.810 W/m ² /K
External fluid temperature	298.20 K

CFD Simulation Results

Results of the simulation study as seen in tables 9 - 12 reveal that the maximum heat flux is 20021.8 W/m², and this value occurs at the crucible pot. This is due to the thermal conductivity of the copper material used in making the crucible pot. The refractory wall is next with a value of 3311.4 W/m², while the casing is least with a value of 1566.5 W/m². The average heat flux is seen to be least in the crucible pot which implies that the transfer of heat energy from the pot to its immediate surrounding is minimal. The average heat flux is highest in the refractory wall and least in the crucible pot. A reason for this observation would be as a result of the increase in the total thermal resistance

offered to the flow of the heat energy as it travels from the combustion chamber towards the surroundings. Figures 10 and 11 show a graphical representation of the heat flux within the furnace.

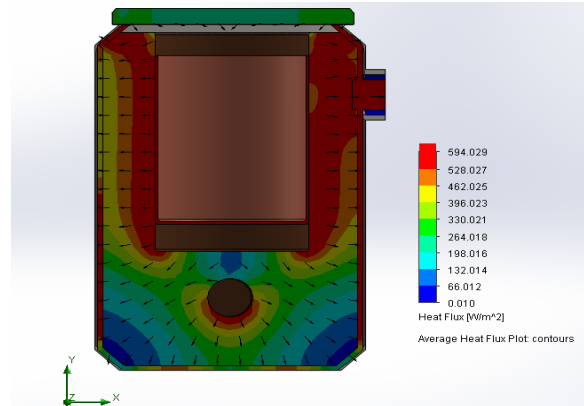


Figure 10: CFD average heat flux plot.

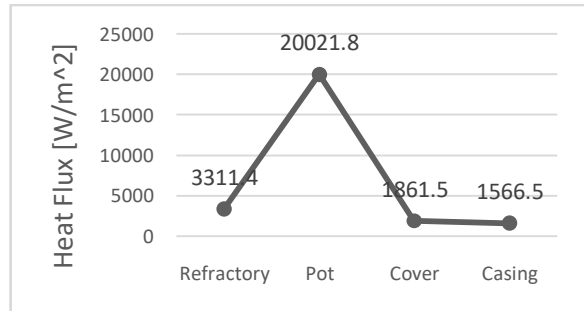


Figure 11: Maximum Heat flux variation across crucible components.

Table 9 shows results for the CFD run on the crucible casing. The result indicates that during the furnace operation, the temperature of the crucible casing is expected to rise from 293.3 K to an average value of 313.2 K, while absorbing 116.9 Joules of heat energy passing through the refractory wall per second.

Table 9: CFD result of crucible casing

Local Parameter	Min	Max	Ave	Surface Area [m ²]
Surface Heat Flux [W/m ²]	-	1566.5	-10.7	10.91
Temperature (Solid) [K]	301.8	324.8	313.2	10.91
Heat Transfer Rate [W]	-	-	-116.9	10.91

The CFD result for the crucible cover as seen in table 10 show that the cover is expected to raise in temperature from its initial value of 293.2 K to an average value

of 301.1 K. This means that a temperature rise of 7.9 K is expected as it transfers 116.98 joules of heat energy from the furnace to the surrounding per second. This is the reason why its temperature is lower than that of the casing although both are made of the same material (mild steel).

Table 10: CFD result of crucible cover

Local Parameter	Min	Max	Ave	Surface Area [m ²]
Surface Heat Flux [W/m ²]	-1535.3	1861.5	81.2	1.44
Temperature (Solid) [K]	298.6	307.9	301.1	1.44
Heat Transfer Rate [W]	-	-	116.98	1.44

The CFD result for the refractory wall as seen in table 11 reveals that the wall will have a maximum temperature of 1143.5 K, and an average value of 776.8 K. The wall would absorb approximately 2.2 KJ of generated heat energy from the combustion chamber. This accounts for the rise in the simulated input temperature from 855 K to 1143.5 K.

Table 11: CFD result of crucible refractory

Local Parameter	Min	Max	Ave	Surface Area [m ²]
Surface Heat Flux [W/m ²]	-20021.7	3311.4	-603.5	3.66
Temperature (Solid) [K]	301.8	1143.5	776.8	3.66
Heat Transfer Rate [W]	-	-	-2206.6	3.66

Table 12 shows the CFD result for the crucible pot. It is observed that the average temperature for the pot during the furnace operation is expected to be 1131.4 K. this value is higher than that of its immediate surrounding (refractory wall) which is at 776.8 K. This is due to the high thermal conductivity of the copper material used in making the crucible pot, and the 2.2 KJ of heat energy absorbed by the refractory wall used to heat up or reduce the heat loss rate in the crucible pot.

The result also shows that there is a flow of heat energy from the pot to its immediate surrounding as a result of its higher temperature, but however, the rate at which

this occurs is at a negligible value of 0.002 W/m². At this temperature of 1131.4 K, the crucible furnace can effectively melt aluminum which has a melting temperature of 933 K. The CFD result also shows that the heat generated within the combustion chamber will not melt the crucible pot since the prevailing temperature is less than the melting temperature of copper.

Table 12: CFD result of crucible pot

Local Parameter	Min	Max	Ave	Surface Area [m ²]
Surface Heat Flux [W/m ²]	-1036.5	20021.8	0.002	3.28
Temperature (Solid) [K]	1117.5	1151.99	1131.4	3.28
Heat Transfer Rate [W]	-	-	0.0056	3.28

Figure 12 shows the CFD average temperature plot of the crucible. It is seen that areas around the crucible pot have higher temperature values and the temperature reduces as the heat energy travels through the refractory wall.

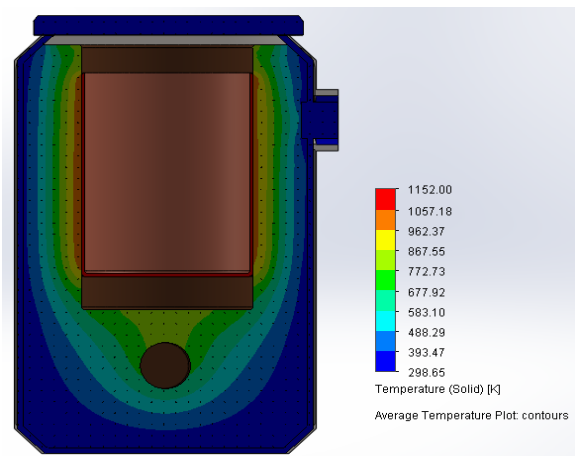


Figure 12: CFD average temperature plot.

CONCLUSION

The study carried out a thermal design of a crucible furnace using CFD technique. A CFD domain was set up, and simulation parameters such as mesh analysis, material settings and boundary conditions were applied. The study revealed that heat generated from the fuel combustion is sufficient to melt Aluminum. Also, the average temperature of the refractory wall suggests that the refractory

would be able to withstand the thermal stresses induced by the temperature. The temperatures of the casing and cover suggest that deformation arising from furnace operation will be quite negligible, and that no hazard is posed to both the foundry operator and the diesel fuel since the maximum external temperature of 313.2 K is less than the flash point of diesel fuel which ranges from 325 K to 369 K. ^[4]

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