Thermal Reduction on Surface of Launch Tube with Isothermal Natural Convection

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***Abstract*—**Launch tube is a key component of Rocket-Launcher. It gets a great impact of rocket's exhaust gas. Due to extremely high temperature of the thrust during launch transferred to launch tube, surface coating of launch tube applied with thermal barrier coating is damaged. Not only the appearance, but also the life time of launch tube is shorten because of rust after the coating removed. To increase life time of the thermal barrier coating and the launch tube, the temperature on the launch tube surface has to be decreased as fast as possible. This study utilizes the air gap to transfer the heat from inside of the tube to the air. In addition, the launch tube with a small hole on the top is presumed to induce the natural convection due to the density difference between air gap (hot) and surrounding air (cold) and release the heat from the structure. For preliminary study, two-dimensional launch tube with air gap is modeled with horizontal concentric cylinder for simulation. The parameters of this study are outside diameter of the launch tube and heat release hole's diameter. With Design of Experiment approach, sets of parameters are defined. The result shows heat flux at each set of parameters and also the temperature distribution along radius in comparison. The graph of radius versus temperature shows that the relation becomes linear at steady state. The flow in the middle of air gap has the maximum flow velocity. The heat flux not only depends on the size of air gap but also the direction of the flow.

***Keywords*—**Launch tube, Thermal reduction, Air gap, Natural convection, Horizontal cylinder.

I. Introduction

LAUNCH tube is the Rocket Launcher's device which carries and positions the rocket to the firing angle. In launching process, the temperature inside the tube suddenly increases. The heat from rocket's exhaust gas quickly transfers to the outer surface of launch tube via conduction and therefore the thermal barrier coating is damaged which also affect on its appearance. Moreover, exposed areas of the launch tube made of mild steel start to be corroded by rust. For these reasons, the thermal energy has to be released from the structure as fast as possible.

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The launch tube has cylindrical-shape with spiral groove inside along the axis. The designed shape for this study is the launch tube covered with a larger tube. The space between the launch tube and the cover tube is called air gap. With the air gap, the temperature on the outer surface painted with thermal barrier coating is less than the original design. To release the heat from the air gap, the outer tube is bored on the top in order to allow the hot air to leak out and replaced with the cold air from outside. This fluid (air) motion occurs from density difference between hot and cold air which is called natural convection heat transfer.

Natural convection between horizontal concentric cylinders is one of the primitive free convection in enclosed space models. The temperature gradient causes the density difference of the fluid that drives the natural convection. The phenomena of heat transfer across the fluid; in this case is air gap, depends on viscous forces and buoyancy forces that is corresponding to Rayleigh number. However, from literature review, the natural convection of horizontal annulus with hole still does not exist.

This study presents the thermal reduction on launch tube's surface after firing. The 2-D horizontal concentric cylinder with hole is used for simulation model in Transient Computational Fluid Dynamics (CFD). The diameter of hole on the top of cylinder is varied from 20 mm. to 50 mm. and the diameter of outer cylinder from 650 mm to 660 mm. The air inside launch tube is set to be 1400 Kelvin at initial condition. The outer surface temperature is kept constant (isothermal) at 300 Kelvin with Rayleigh number from 365 to 1837 and Prandtl number 0.7.

II. Free Convection

Free convection or natural convection is heat transfer which the fluid motion generated by the difference of fluid's density due to the temperature gradient. The convection motion set up as a result of the buoyancy force instead of external force in forced convection. The factors affecting heat transfer by free convection and having physical significance are presented in dimensionless parameters in the following section.

A. Dimensionless Parameters of Free Convection

Grashof number (Gr) represents the ratio of the buoyancy force to the viscous force acting on the fluid. At high Grashof numbers, the boundary layer is turbulent and become laminar at low Grashof numbers. The transition from laminar to turbulent flow is governed by critical value of the Grashof number.

$$Gr = \frac{g\beta\delta^3 (T_s - T_\infty)}{\nu^2} \quad (1)$$

where
- g Gravity acceleration (m/s^2)
- β Thermal expansion coefficient (1/K)
- δ Gap thickness (m)
- T_s Surface temperature (K)
- T_∞ Bulk temperature (K)
- ν Kinematic viscosity (m^2/s)

Prandtl number is the ratio of molecular diffusivity of momentum to molecular diffusivity of heat which is defined as

$$\Pr = \frac{\nu}{\alpha} \quad (2)$$

where α Thermal diffusivity (m^2/s)

For small Prandtl number, the heat diffuses very quickly compared to the velocity (momentum) which means the conductive transfer is strong. On the other hand, the convective transfer is strong for high Prandtl number.

Rayleigh number is another dimensionless number which is the product of Grashof number and Prandtl number. Hence the Rayleigh number itself may also be viewed as the ratio of buoyancy forces and (the product of) thermal and momentum diffusivities. Instead of Grashof number, Rayleigh number is used to correlate heat transfer in natural convection.

$$Ra = Gr \Pr \quad (3)$$

Nusselt number is the ratio of heat transfer by convection to conduction across the fluid layer. Then the value of the Nusselt number is equal to unity when there is no convection or the heat transfer is by pure conduction. The larger value of the Nusselt number implies enhanced heat transfer by convection. Below is the general formula of Nusselt number

$$Nu = \frac{hL}{k} \quad (4)$$

where
- h Convective heat transfer coefficient ($W/m^2.K$)
- L Characteristic length (m)
- k Thermal conductivity (W/m.K)

These principal dimensionless parameters are derived from considering free convection on a vertical plate with the assumption that the boundary-layer flow is steady and laminar. However for the natural convection in enclosed space, it becomes more complicated problem. The formulations have to be derived from experimental data. References from literature review and empirical correlation will be presented in following section.

B. Empirical Correlation for Horizontal Concentric Cylinder

As mentioned, the behavior of natural convection is mainly determined by Rayleigh Number (Ra). Besides, in the case of horizontal concentric cylinder, Radius Ratio (RR) has to be considered too. For example, refer to the study by El-Sherbiny and Moussa [1], lamina natural convection in the air annular gap between two infinite horizontal isothermal cylinders using numerical method. The result shows that the laminar boundary layer regime starts at higher Ra or larger RR.

From literature review, the experimental data of free convection in enclosed space of horizontal annulus with hole is not available. The empirical correlation of simple horizontal concentric cylinder is used to approximate the behavior of the heat transfer over the range $10^2 < \mathrm{Ra}^*_{\mathrm{cyl}} < 10^7$

$$\frac{k_{eff}}{k} = 0.386\left(\frac{\Pr}{0.861+\Pr}\right)^{1/4}(Ra^*_{cyl})^{1/4} \quad (5)$$

where

$$Ra^*_{cyl} = \frac{[\ln(D_o/D_i)]^4}{\delta^3(D_i^{-3/5}+D_o^{-3/5})^5} Ra_\delta \quad (6)$$

$$Ra = \frac{g\beta(T_i - T_o)\delta^3}{\nu^2}\Pr \quad (7)$$

$$\delta = \frac{(D_o - D_i)}{2} \quad (8)$$

D_i, D_o Diameters of the inner and outer cylinders respectively

C. Flow Characteristic

Since the air gap (δ) is very small comparing with the size of launch tube and the maximum outer diameter of the tube is limited at 660 mm, the highest Rayleigh number calculated from (7) is still less than the critical value. From reference, the heat transfer of horizontal annulus with this Rayleigh number is in the form of pure conduction. This paper presents the affect of hole on heat transfer which induces the natural convection through the hole on the top of the cylinder.

III. Problem Analysis And Simulation

This study covers the range of outside diameter from 650 to 660 mm with constant inner diameter 632 mm. The diameter of drilled hole is varied from 20 to 50 mm. At initial condition, the temperature of the air inside the annulus is equal to 1400 Kelvin and the outer surface of cylinder is 300 Kelvin isothermal surface.

From above design variables, using Design of Experiment (DOE) approach, the design space is defined in Table I. All replicated sets of Design Parameters are removed because the error from experimental setting is not considered in computational simulation.

TABLE I
DESIGN PARAMETERS FOR SIMULATION

Launch Tube diameter (mm)	Hole diameter (mm)
650	20
650	35
650	50
655	20
655	35
655	50
660	20
660	35
660	50

After defining the design space, the simulation model is created by using 2D quadrilateral mesh which covers the area of air inside the tube, air gap and air above the hole as presented in Fig. 1. As the focus area, the elements near surfaces of inner and outer cylinders are meshed in small size. The outer diameter is varied follow the launch tube's diameter of the design space and the same with the hole's diameter.

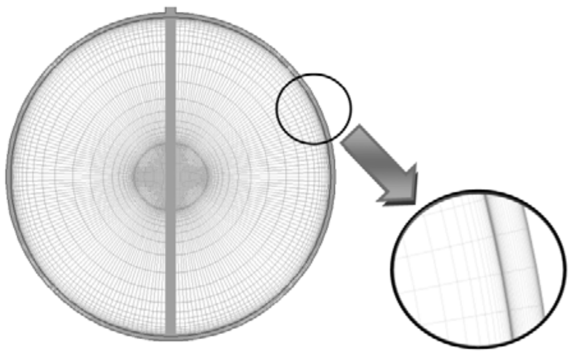


Fig. 1 Two Dimensional Meshed Model

IV. RESULT AND DISCUSSION

In this part, the numerical results of temperature distribution, temperature difference and heat flux are investigated. Since graphs of temperature versus radius ratio have the same trend in every cases, only the plot belongs to the model with outer diameter 650 mm and hole diameter 20 mm is presented. Radius ratio is a dimensionless parameter defined in (9). Radius ratio equals to 0 at the surface of inner tube and 1 at the surface of outer tube.

$$\text{Radius Ratio} = \frac{(R - R_i)}{(R_o - R_i)} \quad (9)$$

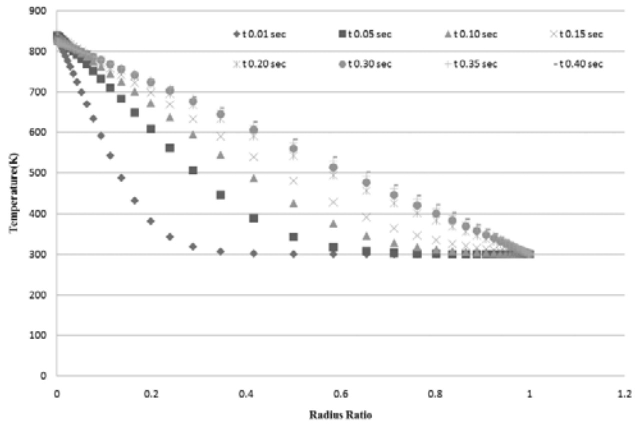
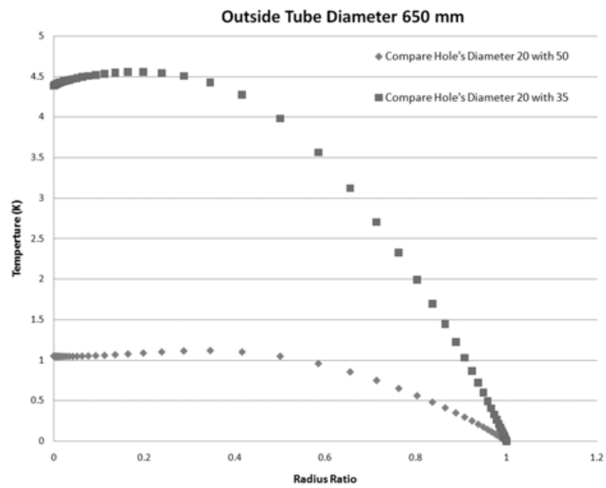


Fig. 2 Temperature Distribution of Tube OD 650 mm. hole diameter 20 mm. at time 0.01 to 0.4 sec

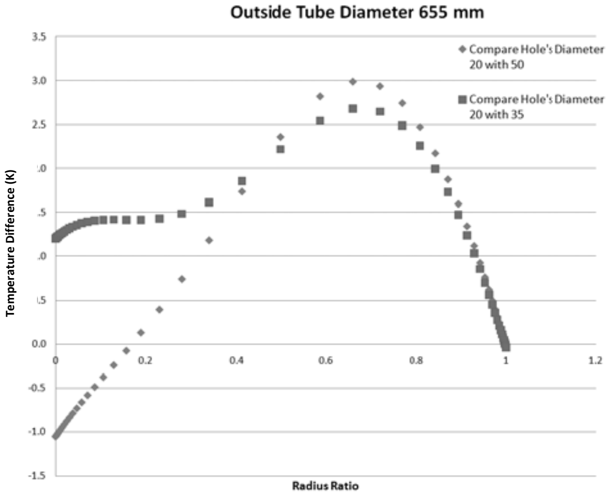
Fig. 2 shows the temperature distribution from the surface of inner tube to the outer tube along the horizontal axis (0 degree). The temperature gradually changes from non-linear curve at the initial time to linear curve at steady state. From the data, the maximum temperature slightly changes after 0.40 sec, it is assumed to be steady at this point. With this reason, the plot shows the temperature distribution from time 0.01 sec to 0.40 sec. At steady state, the linear relation means that the heat transfer is in conductive form. The maximum temperature on the inner surface is about mean temperature between 1400 K and 300 K. The minimum temperature occurs on the isothermal surface of outer tube which is controlled at 300 K.

Comparing temperature distribution at different hole's diameters, the results of temperature difference versus non-dimensional radius ratio are plotted in Fig. 3. Temperature distribution of tube with hole's diameter 20 mm is set as reference. To compare with hole's diameter 35 mm of the same tube, the temperature difference is calculated from (10) which is the same for diameter 50 mm.

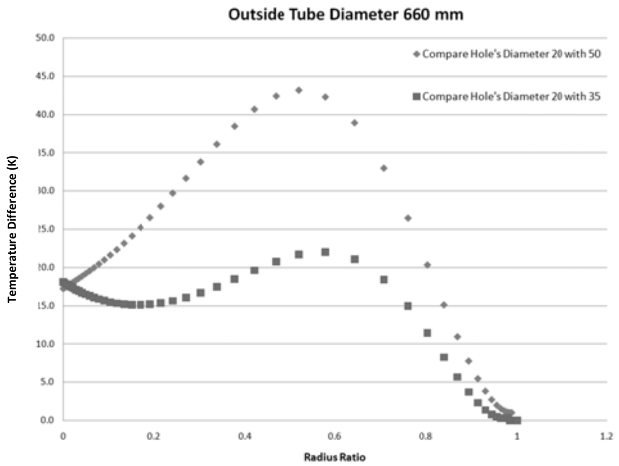
$$\text{Temperature Difference} = T_{20} - T_{35} \quad (10)$$



(a)



(b)



(c)

Fig. 3 Temperature Difference of Tube OD 650, 655 and 660 mm.

From Fig. 3 (a) - (c), trends of graphs are different which means that the hole's diameters have dissimilar effect on the heat transfer for each outer diameter of the launch tube. Temperature differences of launch tube's diameter 650 and 655 mm, Fig. 3(a) and (b), are less than 5 K which are not significant comparing with maximum temperature. While the temperature difference is observed for launch tube's diameter 660 mm. From Fig. 3(c), the highest temperature difference between hole's diameter 20 mm and 50 mm is 43.18 K. From these results, not only the diameters of launch tube and hole that affect the heat transfer phenomena but also the motion of the flow. To understand physics of heat transfer in each case, the flow velocity has to be investigated in further study.

Fig. 4 shows the surface plot of heat flux with launch tube's diameter and hole's diameter obtained from simulation. The plot reveals that launch tube with diameter 650 mm has the maximum heat flux and it has the same trend for every hole's diameter. At constant launch tube's diameter, the heat flux slightly changes at different hole's diameters.

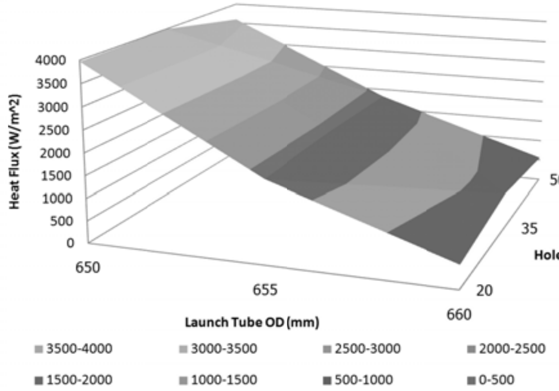


Fig. 4 Heat Flux versus Launch Tube's Diameter and Hole's Diameter

V. Conclusion

During rocket launch, the exhaust gas with 1400 K causes the increasing in the temperature on the launch tube in short period of time. The extreme heat damages surface coating and then the rust occurs. The basic heat transfer that release heat from the structure is by natural convection.

The horizontal concentric cylinder is used as comparative model for calculation. Then natural convection is studied by two-dimensional transient CFD.

The results show that different hole's diameter has different effect on each launch tube's diameter. However, the temperature difference becomes significant at the large launch tube. On the other hand, heat flux is minimum at the largest launch tube. To explain these behavior, the flow motion and flow velocity have to be investigated in extended 3D study.

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