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Transient Thermal Analysis of a Thermo-Flask

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Original Research Article

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Abstract: The transient heat transfer of a thermo-flask container is presented using the lumped capacitance method with the assumption that there is no temperature gradient between the container's wall and the fluid. The thermos-flask is considered partially filled. The fluid in the flask is reduced due to venting of the fluid. The mass of the vented fluid can be evaluated by considering the heat transfer from the container to the surrounding. It is found that the partially filled thermos-flask influenced the transient temperature characteristics of the thermo-flask.
Keywords: Heat transfer, Lumped parameter analysis, Transient heat transfer, Thermo-flask, Venting.

INTRODUCTION

The storage of cryogenic liquids is required for space launch vehicle and space [1]. The tank is needed to thermally analyse when partially filled with liquid cryogenic tank. Figure 1 depicts a container with a partially filled fluid at a given time. The thermos-flask tank is having heat gain from the surrounding. The heat transfer from the ambient cause's evaporation of the fluid in the container, and therefore, the container is provided with pressure relief valve with adequate venting arrangement. Temperature gradient within the fluid in the thermo-flask is neglected. A simple and convenient approach, termed the lumped capacitance method [2] and [3], is used to determine the variation of temperature in the stored fluid in the container as a function of time. Temperature of the fluid in the tank is spatially uniform at any instant during a transient heat transfer process.

Nomenclature

A = area of (thermo-flask) container, m^2
C_P = specific heat, J/kg K
h = overall heat transfer coefficient, W/m^2 K
h_{fg}= latent heat of vaporization, J/kg
m = mass of fluid, kg
m_v = vented, depleted or drained fluid, kg
t = time, s
T = temperature, K
Subscripts
i = initial
s = saturation
∞ = ambient

The literature survey shows that the partially filled thermo-flask has not been analyzed. The objective of the paper is to apply the lumped capacitance model for determining the time dependence of the temperature within the fluid stored in the thermo-flask, the heat transfer between the fluid and its surrounding and the mass of the vented fluid during a transient thermal process.

Analysis

It is assumed in the analysis that the inner wall of the container will have same temperature as that of the fluid. Terms for kinetic and potential energy are small as compared to the thermal energy stored inside the tank; therefore, they are neglected in the energy balance of the tank. The work done by the venting fluid is neglected since the pressure rise is small in the thermo-flask. The transient temperature response is obtained by formulating an overall energy balance on the thin wall fluid container. When the tank temperature exceeds the saturation temperature T_S, we have neglected the latent heat of evaporation, for simplicity. The energy balance relates the rate of heat transfer at the surface to the rate of change of the internal energy, which can be written as.

$$mCp\frac{dT}{dt} + H\frac{dm_v}{dt} = hA(T_\infty - T) \quad (1)$$

where H is the enthalpy of the vented fluid. Equation (1) is valid when $T < T_S$ and $m_v = 0$. When $T > T_S$, the second term on the left-hand side takes care of the depleted mass of the fluid. We have considered in the formulation of Eq. (1) that the energy went out from the cryogenic tank is neglected considering small amount fluid is vented out with a very small velocity at the vent. Both the cases are accounted in Eq. (1). Where T_S is the saturation temperature of cryogenic fluid in the tank. The equation for the mass of the vented fluid m_v can be formulated as

$$m_v = \int_0^t \frac{hA}{h_{fg}}(T_\infty - T_S)dt \quad (2)$$

where h is equivalent overall heat transfer coefficient, that takes into account the thermal resistances of conduction, convection, and radiation between ambient temperature T_∞ and saturation temperature T_S. The initial condition is

$$T = T_i \quad \text{at} \quad t = 0 \quad (3)$$

Introducing the temperature difference $\theta = (T - T_\infty)$ and Eq. (1) becomes

$$\frac{mCp}{hA}\left(1 - \frac{m_v}{m}\right)\frac{d\theta}{dt} = -\theta \quad (4)$$

Separating the variables and integrating Eqs. (2) and (4), we get

$$m_v = \int_0^t \frac{hA}{h_{fg}}\theta dt \quad (5)$$

$$\frac{mCp}{hA}\int_{\theta_i}^{\theta}\left(1 - \frac{m_v}{m}\right)\frac{d\theta}{\theta} = -\int_0^t dt \quad (6)$$

Equations (5) and (6) are nonlinear and coupled due to presence of m_v, and hence have to be solved numerically in order to obtain the mass of the vented fluid and temperature of the fluid as a function of time. We consider here a simple case to illustrate the effect of m_v on the transient thermal response. For a constant value of m_v, the exact solution of Eq. (6) is

$$\frac{\theta}{\theta_i} = e^{-\left\{\frac{hA}{(m - m_v)Cp}\right\}t} \quad (7a)$$

Equation (7a) can be rewritten in the following form in terms of m_v/m, which is mass of the vented fluid as

$$\frac{\theta}{\theta_i} = e^{-\left\{\frac{hA}{m\left(1 - \frac{m_v}{m}\right)Cp}\right\}t} \quad (7b)$$

The heat transfer process is influenced by the factor $(m - m_v)/A$, where A is the area of the container and not strongly dependent on the volume of the vessel. If the m_v is zero, the tank is fully filled with the fluid. It is important to mention here that the container area A is not changed.

RESULTS AND DISCUSSION

Let us consider here a case when the tank is fully filled with fluid with the initial temperature T_i. The transient temperature response is worked out for different values of (hA/mC_P). From this value, the corresponding *(m_v/m)* values can be calculated using Eq. (7b). For varying *(m_v/m),* the temperature can be read from Fig. 2 as step changes in the values of the parameter (hA/mC_P). The transient temperature response is depicted in Fig. 2 for various values of the *(hA/mC_P)*. The temperature inside the partially filled tank (m_v/m) $= 0.3$ decreases rapidly as compared to (m_v/m) $= 0.2$ as observed in the figure. At $t = 5s$, the values of (θ/θ_i) $= 0.61$ and 0.28 are for (hA/mC_P) $= 0.10$ and 0.25, respectively, as seen in Fig. 2. It shows that the temperature reduction is lower if the tank is not fully filled. The analysis will be extended to couple the venting [4-7] with heat transfer in conjunction with experimental data. The present analysis will be further extended to take into consideration cryogenic fluid boil-off time as design parameters for the tank performance.

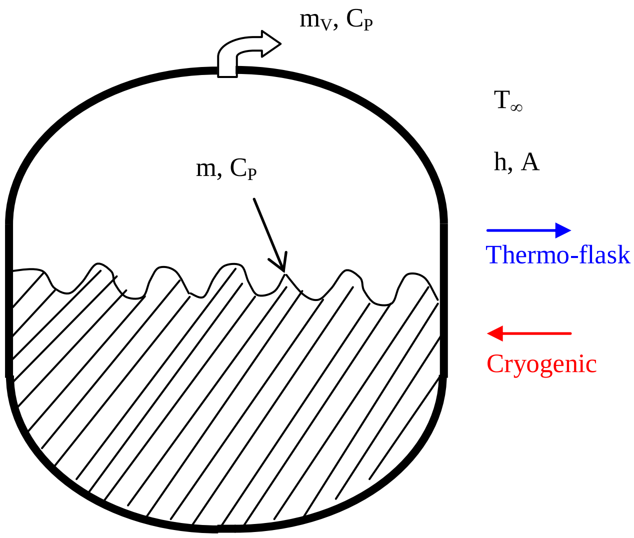

Fig-1: Thin wall container

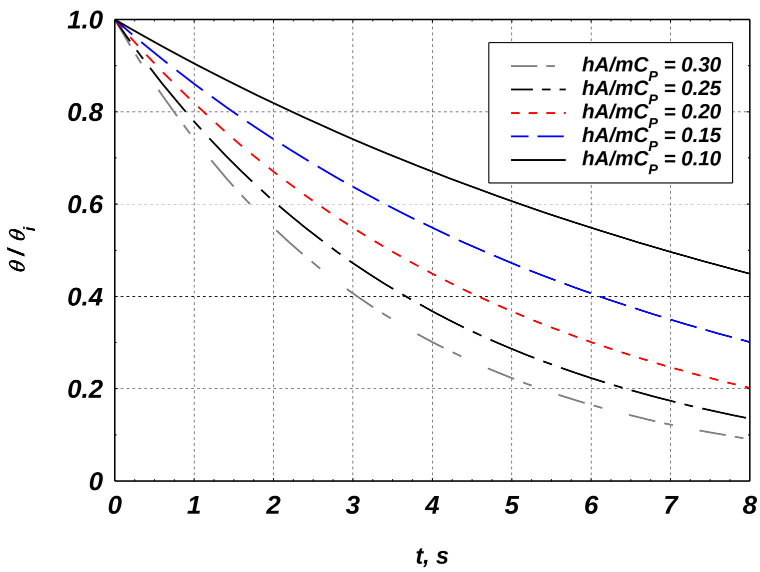

Fig-2: Transient temperature response for various values of *hA/mC_p*

CONCLUSIONS

The transient temperature response of the thin wall container is presented using the lumped capacitance method with the assumption that there is no temperature gradient between the container's wall and the fluid. The mass of fluid in the tank is considered as a function of time, which is reduced due to venting of the fluid. The mass of the vented fluid can be evaluated by considering the heat transfer from the container to the surrounding. There is no change in the area of the container. The temperature of the fluid in the container is reduced if the container or the thermo-flask is not fully filled.

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