

Thermal Analysis of Urea Tank Solution Warm Up for Selective Catalytic Reduction (SCR)

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ABSTRACT

Due to the stringent requirements to reduce the tail pipe emissions of NO_x , Selective Catalytic Reduction (SCR) systems are used to remove NO_x using ammonia. When a urea solution is injected into the exhaust system, urea will undergo hydrolysis and decomposition reaction that produces ammonia. At the catalyst surface, ammonia will react with the exhaust gases to convert NO_x into nitrogen, N_2 and water, H_2O . One of the challenging problems is to make sure the urea solution is available for the SCR system at cold start conditions. At extreme cold temperatures, the urea solution will begin to freeze at -12°C . At the start up of a vehicle under such low ambient temperatures, a heating system is used to provide the heat required for melting the frozen urea.

Therefore, there will be a time lag between the vehicle start up and the availability of urea solution to the SCR system. The response time of the urea tank heating system to deliver adequate quantities of urea solution depends on the initial temperature, mass of the frozen urea, heating system design and dimensions. In this paper, a transient thermal analysis model describing the heating process is developed. Test data for the warm up time at different test conditions are also presented.

INTRODUCTION

Selective Catalytic Reduction (SCR) of NO_x with ammonia is the most selective reaction for the removal of NO_x in presence of excess oxygen. Stationary

engines and other NO_x sources have been using ammonia and urea based SCR systems for many years. This has been well documented for stationary applications [1-7]. For mobile applications, urea SCR is currently the only proven NO_x after-treatment for diesel engines that gets anywhere close to the severe NO_x limits that EPA proposes. Though the SCR system is effective in removing NO_x , its performance depends on the availability of urea solution at the exhaust injection point. However, urea solution starts to freeze at -12°C which may cause the SCR system to be inoperative if the urea solution becomes frozen enough that it does not have enough liquid to react with the nitrogen oxides in the exhaust gas stream. This range of temperature is common in North America during winter time. Though the regulations do not require the SCR system to operate instantly at temperatures below -12°C , it is still required that the system should be active within reasonable time. Therefore, some means of heating the frozen urea are required. The heating system should allow the frozen urea to thaw and provide continuous supply of liquid urea. In this paper, a mathematical model is developed in order to describe the melting of frozen urea. The model is transient and allows determination of thawing rate of urea as function of time. Experimental test data which were collected during initial phases of design are used to verify the mathematical model accuracy.

MATHEMATICAL MODEL

Although several studies have been conducted [8-10] to investigate phase change of different materials, there are a very limited number of publications related to studying the thawing process of a frozen urea solution during vehicle cold start conditions. Previous work related to phase change were mainly focused on phase change applications for energy storage or phase transformation for environmental or metallurgical applications. The analysis of heat transfer problems in melting and solidification processes, called moving boundary problems in scientific literature, is especially complicated due to the fact that the solid-liquid boundary moves depending on the speed at which the latent heat is absorbed or released at the phase separation.

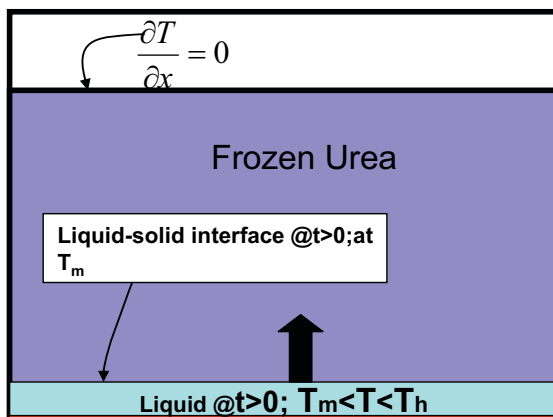


Figure 1. Description of urea tank thermal model

MODEL ASSUMPTIONS

The urea tank model is described in figure 1. A heat source is placed near the bottom of the tank where heat can be provided by an electric heating element or by passing engine coolant through a heating coil. Electric heating has the advantage of providing instant heat into the urea tank regardless of the duty cycle. However, it may be a burden on electric power supply. In truck applications, a water heating system is the preferred method for heating the urea tank. However, using water heating system will introduce additional time lag caused by time required for the engine coolant to warm up, the heat transfer from the engine coolant to the coil inner surface, conduction through the coil wall and finally heat transfer from the coil outer surface to the surrounding urea. The response of the heating system in this case depends on several factors including engine coolant flow rate, engine coolant temperature, coil wall thickness and thermal conductivity as well as thermal properties of engine coolant and urea. Once the surface temperature of the heating element exceeds the melting point of the frozen urea, thawing will start to take place. Heat will

then be transferred by conduction through the melted layer immediately next to the heating element. Therefore, a temperature gradient will be established between the solution adjacent to the heating element and the solution at the solid-liquid interface. This difference in liquid phase temperatures may also cause free convection to take place. However, it has been estimated by Wiesche [11], that free convection has limited effect on the heat transfer process within the liquid phase. This assumption is validated by investigating the Raleigh number in next section.

THERMAL MODEL FOR SOLID UREA

The conduction equation within the solid phase is given by Holman [12]:

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial x^2} \right) \quad (1)$$

The temperatures of both the liquid and solid phases along the interface surface are equal to the melting point, which leads to the following boundary condition:

$$T_s = T_l = T_m, \text{ at } x = x_{sl}^*(t) \quad (2)$$

Where,

x_{sl}^* = The dimensionless position for the liquid-solid interface.

L = The latent heat of fusion

Energy balance at interface surface [13] provides the following equation which relates the instantaneous position of the interface surface to the temperature gradient through the solid and liquid phases:

$$L\rho \frac{\partial x_{sl}^*}{\partial t} = k_s \frac{\partial T_s}{\partial x} - k_l \frac{\partial T_l}{\partial x} \quad (3)$$

For most of the time, the solid phase at the top of the tank will remain frozen since the surrounding ambient is usually at the same initial temperature as the frozen urea. Therefore, heat transfer between the top of the frozen urea and the ambient can be assumed negligible which leads to the following boundary condition:

$$\frac{\partial T_s}{\partial x} = 0, \quad \text{at } x = \infty \quad (4)$$

Boundary Condition at the Liquid Phase

It is assumed that the lower surface of the urea solution is at a constant temperature T_h or:

$$T = T_h, \text{ at } x = 0 \quad (5)$$

This assumption is based on the following analysis for a heating system using engine coolant.

The heat conduction equation through the heating coil wall can be described by the following equation:

$$\frac{\partial T_w}{\partial t} = \alpha_w \left(\frac{\partial^2 T_w}{\partial x^2} \right) \quad (6)$$

Subject to the following initial and boundary conditions:

$$T_w = T_i, \text{ at } t = 0 \quad (7)$$

At the inner surface ($x = 0$):

$$-k_w \frac{\partial T_w}{\partial x} \Big|_{x=0} = h_i (T_c - T_w) \Big|_{x=0} \quad (8)$$

At the tube outer surface ($x = th$), where th is the tube wall thickness:

$$-k_w \frac{\partial T_w}{\partial x} \Big|_{x=th} = h_o (T_w - T_l) \Big|_{x=th} \quad (9)$$

where,

T_s = Solid phase temperature

T_l = Liquid phase temperature

T_w = Heating coil wall temperature

T_i = Initial temperature

k_w = Coil wall thermal conductivity

k_s = Solid phase thermal conductivity

k_l = Liquid phase thermal conductivity

h_i = Coolant side heat transfer coefficient

h_o = Outer side heat transfer coefficient

ρ = Density

C_p = Specific heat

α = Thermal diffusivity ($\frac{k}{\rho C}$)

α_s = Solid phase thermal diffusivity ($\frac{k_s}{\rho_s C_s}$)

α_l = Liquid phase thermal diffusivity ($\frac{k_l}{\rho_l C_l}$)

In the above equations, for a heating coil with thin wall and high thermal conductivity, the temperature gradient throughout the wall is negligible. This leads to the following equation:

$$h_i (T_c - T_w) = h_o (T_w - T_l) \quad (10)$$

Therefore, the liquid temperature T_l can be evaluated from the following equation:

$$T_l = T_w - \frac{h_i}{h_o} (T_c - T_w) \quad (11)$$

The wall temperature T_w can be evaluated from the following equation:

$$T_w = \frac{\left(\frac{h_o}{h_i}\right) T_l + T_c}{1 + \left(\frac{h_o}{h_i}\right)} \quad (12)$$

Since the internal heat transfer coefficient h_i is much higher than the outer heat transfer coefficient h_o , it can

be concluded that $\frac{h_o}{h_i} \approx 0$ and $T_w \approx T_l \approx T_c$.

To investigate the change in engine coolant temperature with time, the coolant temperature can be evaluated from the following equation [14] for fluid flow inside a long round tube:

$$\rho C_p v_z \frac{\partial T_c}{\partial z} = +k \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T_c}{\partial r} \right) \right] \quad (13)$$

From equation (13), it can be concluded that the coolant temperature at a given location along the pipe length is steady and that the liquid temperature at the tube wall is also constant. This conclusion is based on the assumption that the engine coolant flow rate and coolant temperature are constant. This justifies the use of a constant boundary temperature for the one dimensional analysis.