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# Thermal Management for Efficient Fast Refill of Compressed Natural Gas

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***Abstract***— As an alternative fuel, compressed natural gas (CNG) plays an important role fueling transportation. Like driving other types of vehicles, drivers of CNG-powered vehicles prefer to refill on-board CNG tanks in a short time, which is referred to as fast refill. Accompanied by a fast pressure increase in the cylinder, temperature will also rise significantly due to re-compression work with limited time for the heat to dissipate. This phenomenon ends with a common problem referred to as under-refill, which means less mass filled than the standards. This article presents a summary of the research works to solve this problem and improve fill efficiency by thermal management. Two-dimensional axisymmetric CFD (computational fluid dynamics) simulations of unsteady, compressible, turbulent flow in fast refill process are conducted. Three different types of thermal management concepts are discussed, including active cooling, pre-chilling and real-time chilling. The results show that thermal management is a promising way to mitigate the under-refill problem with a maximum of 7% increase of fill efficiency achieved by active cooling. These provide guidelines for future research on improving fill efficiency through cooling strategies in which real-time chilling should be firstly focused on.

***Keywords- Compressed natural gas; Fast refill; Thermal management; Computational fluid dynamics***

## I. INTRODUCTION

Natural gas [1] has become an important alternative fuel for transportation. The number of natural gas vehicles (NGVs) has escalated speedily at an annual rate of 24% since 2005 [2] and now it powers roughly 22.4 million vehicles around the world [3]. Due to the comparatively low density, natural gas is carried either as liquefied low-temperature LNG (liquefied natural gas) or as high-pressure CNG (compressed natural gas) with the latter currently having higher market share [4].

For CNG fuelled vehicles, a common problem is under-refill when the on-car gas cylinder is fast filled (<5 mins) at CNG station. It is caused by temperature rise in the filling process followed by earlier reaching the standard pressure. This means less mass of CNG filled as the temperature inside finally recovers to ambient temperature and the pressure inside drops. The temperature rise is a result of the heat generated by recompression work and inadequate time for the heat to be removed out naturally through cylinder wall with material of low conductivity. It is at least about 10ºC above the ambient temperature at the end of fast refill [5]. Fill efficiency is thus typically only 80% for ambient temperature at 20 ºC when the efficiency is defined as the ratio of the actual filled mass to the capacity at the rated pressure and ambient temperature [6].

To mitigate the under-refill problem, the simplest idea is to over-pressurise the cylinder when refilling it, which has a risk of safety issues. The second way that has been considered is to develop good strategy with modified feeding conditions to minimize the re-compression heat. Farzaneh-Gord et al. [7] showed that existing procedure proposed [8] requires appropriate controlling facilities, limiting the applicability. Compared to the above two methods, thermal management is a more promising way to achieve higher filling efficiency, in which cooling technique and strategies are introduced to lower the CNG cylinder's temperature before or during the refilling process. Zhang et al. [9] numerically investigated an active cooling concept and achieved a 7% increase of fill efficiency at the expense of utilizing a simple cooling loop, which shows good prospect for thermal management in improving the fill efficiency of CNG.

There are very few previous studies focusing on thermal management of efficient fast refill of CNGs. The article presents a summary of the work done on thermal management to improve fill efficiency of CNG cylinder, involving three types of thermal management method: active cooling, pre-chilling and real-time chilling. The effects of these methods on thermal behaviour and fill efficiency of the CNG fast refill process are presented and discussed.

## II. NMERICAL MODEL AND THERMAL BEHAVIOUR OF THE FAST REFILL PROCESS

To quantify the temperature rise and its effect on the fill efficiency, a 2-D CFD model is built for the fast fill process, employing ANSYS Fluent®, a commercial CFD package. Gas inside the cylinder is modelled as an axisymmetric flow. For simplicity, the working fluid is pure methane with real

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gas properties determined using the Redlich-Kwong equation of state [10]. The standard k-ε turbulence model with enhanced wall treatment is applied with modified coefficients ($C_{1\varepsilon}$=1.52, $C_{1\varepsilon}$=1.92, $C_{\mu}$=0.09) [11]. As shown in Fig 1, model geometry is based on a type-III cylinder which is one of the four types of cylinder commonly used for natural gas vehicles. The type-III cylinder wall consists of the aluminum liner and the carbon fiber wrap. The dimensions of the cylinder follow the model used by Nahavandi [12]. The gas enters the cylinder through a converging nozzle that has an entrance diameter of 0.01 m and an exit diameter of 0.005 m. Figure 2 shows the unstructured mesh applied in conventional fast filling case. Mesh is refined near the inlet region where there expect big gas property changes and gradients.

A convection boundary condition is imposed on the outer wall of the cylinder with a constant heat transfer coefficient of 10 $W/m^2 \cdot K$, and the ambient air temperature is kept constant at 300 K throughout the filling process. At the inner wall, a no-slip boundary condition is imposed. The initial pressure of the gas inside the cylinder is 2 MPa. A constant total enthalpy boundary condition is applied corresponding to a total temperature of 300 K. A total pressure that linearly ramps from 4 to 20.6 MPa in the first 3 seconds of the fill process and then is maintained at 20.6 MPa for the remainder of the fill. The refill is considered to end at time t when the average gas pressure $p_g(t)$ satisfies the following equation:

$$\frac{p_g(t)-p_i}{p_s-p_i}=95\% \tag{1}$$

where $p_s$ and $p_i$ are the total supply pressure and initial pressure, respectively.

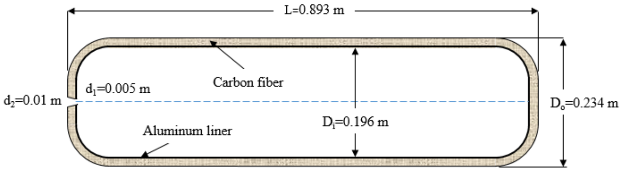

Figure 1. The computational domain for conventional fast filling process

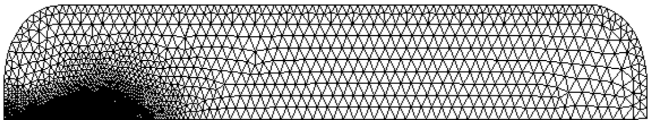

Figure 2. The computational mesh used for fast refill process without cooling

Figures 3-4 present the temporal variation of the average temperature and mass filled, respectively, within the cylinder during conventional fast refill process. The temperature rises quickly in the first 5 seconds, and after that, the temperature increase slows down and ends at a final temperature 29K higher than the ambient temperature. Totally, 3.35 kg natural gas is filled into the cylinder. Potential of reducing the final temperature and increasing the final mass can be seen related to different thermal management concepts.

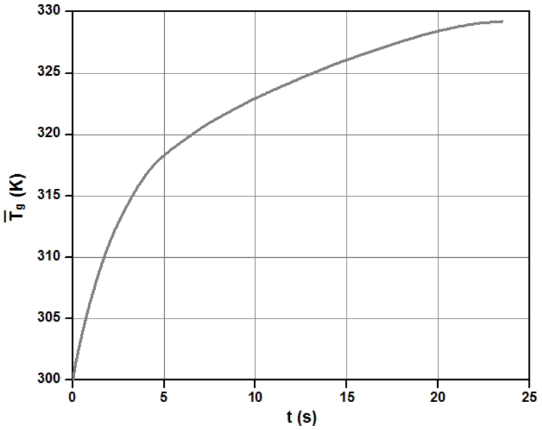

Figure 3. Dynamic change in gas average temperature

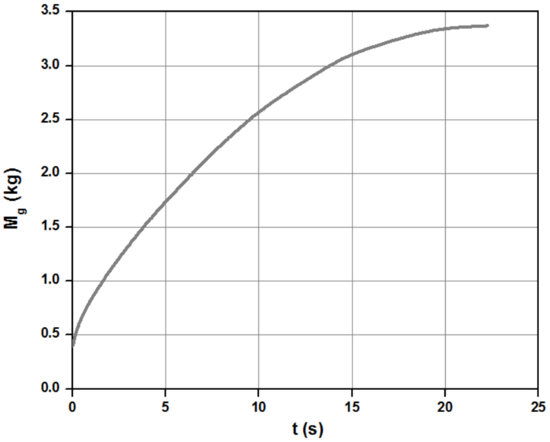

Figure 4. Dynamic change in mass filled

## III. IMPROVING FILL EFFICIENCY BY ACTIVE COOLING

In the concept of active cooling, the natural gas is filled and cooled simultaneously in the filling process with coolant loop used to help remove heat to the ambient environment. There are two important features of the active cooling. The first is that the feeding flow rate of coolant can be adjusted so it can actively adjust the target temperature of the cooling, which is different from some passive heat removal device as heat pipes. The second feature is that the ultimate low temperature it can reach is the ambient temperature.

The heat removal performance of active cooling is investigated by using 2-D axisymmetric CFD simulation on a simplified model with location effects considered. The cooling system is expected to be composed of cooling coils installed inside the cylinder (Fig 5) which are connected to a coolant pump and a heat exchanger, which are not displayed in Fig 5. For simplicity, only the inside cooling coils are considered in the model (Fig 6) and they are placed in the front or back part of the cylinder. A uniform and constant temperature 300 K is applied at the coil surface. It represents the ideal extreme temperature that the cooling loop can reach assuming an ambient temperature of 300K.

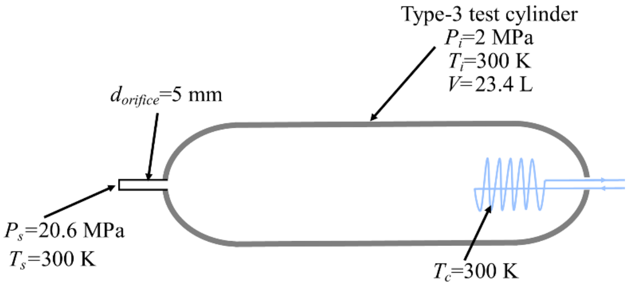

Figure 5. Schematics on the active cooling concept

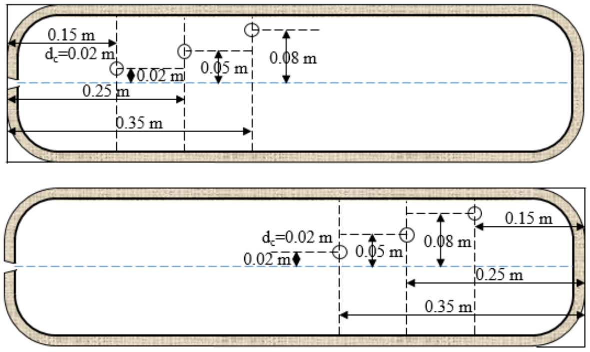

Figure 6. The computational domain for filling process with active cooling in the front and back

Figures 7-8 present the temporal variation of the average gas temperature and mass within the cylinder during the fill, respectively, with active heat removal via the cooling coils in the front and the back. Comparison has been made with conventional fast refuelling without cooling. As shown in Fig 7, different from the monotonic increase of the temperature for the case without cooling, the temperature for the active cooling cases starts to go down after the first 5 seconds' increase. This results from a stronger effect of cooling than that of recompression heating. The maximum average temperatures are 313.3K and 310 K, respectively, for front cooling and back cooling, while the maximum value could be as high as 329K for no cooling. Through active cooling, 7% more mass of gas is filled into a cylinder when cooling happens at the back part of the gas cylinder, while the fill efficiency only increases by 4.5% when the cooling coils are placed at the front. Apparently, fast refill is more efficient when active cooling is conducted in the back of the cylinder. These improvements are accompanied by longer fill time, which, however, is still comparable to that of conventional liquid fuel.

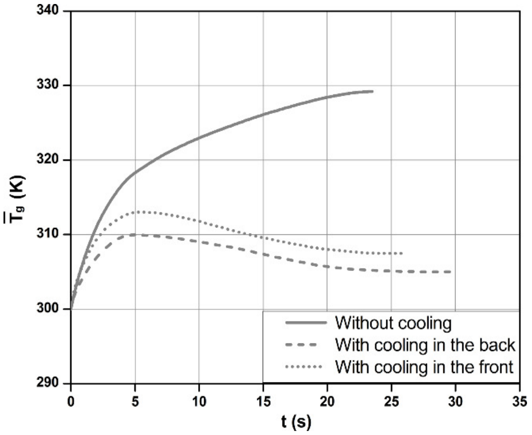

Figure 7. Dynamic change in gas average temperature

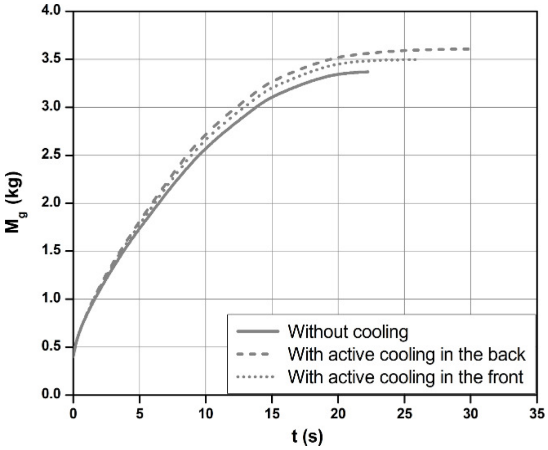

Figure 8. Dynamic change in the mass of gas filled

## IV. IMPROVING FILL EFFICIENCY BY PRE-CHILLING

Although active cooling can help improve the fill efficiency by 7%, there are still two limitations for this method. Firstly, the coolant temperature is no lower than the ambient temperature, leading to limited maximum cooling ability. Secondly, excessively high pressure difference across the coil wall requires material of high mechanical strength and possible leakage will reduce the fuel quality. A new concept named pre-chilling is then considered in this section. As displayed by Fig 9, a pre-chilled mass block made of aluminium alloy is designed to be placed in the back side of the cylinder. There is a coolant circulation to chill the mass to a temperature below the ambient temperature prior to the beginning of gas filling. The chilled mass is then responsible for cooling the gas filled in the filling process. The liquid refrigerant (R134a) from truck air conditioning system [13] can be used to cool down the aluminium mass prior to the filling process.

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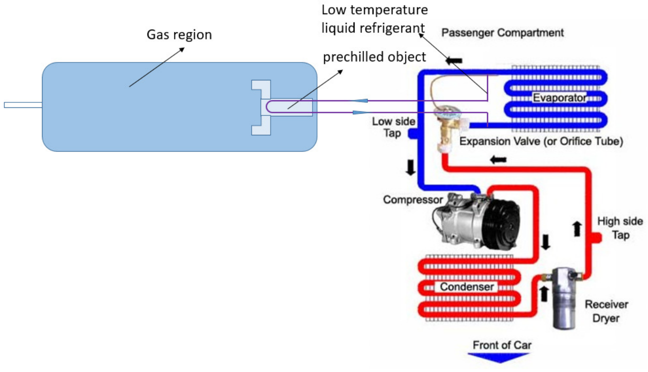

Figure 9. Schematic diagram of pre-chilling achieved by refrigerant circulation

The geometry of model used in simulation is designed with fins, as displayed in Fig 10. The pre-chilled mass takes 5% of the gas volume. Saturated liquid refrigerant flow with temperature of -1.2°C and pressure of 275.79 kPa [14] is used to chill the mass with 4 different refrigerant mass flow rates tested ranging from 0.0035 kg/s to 0.014 kg/s. For comparison, another case is also simulated with a constant temperature boundary condition (-1.2°C) applied at the wall of the channel, which corresponds to infinite flow rate.

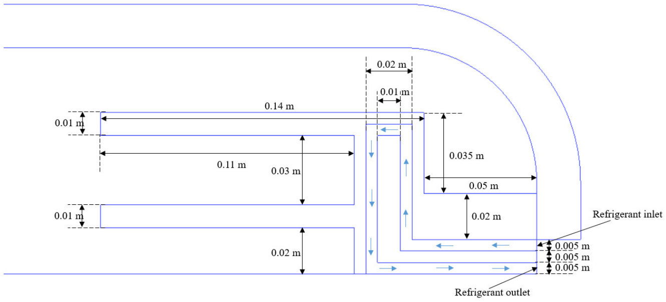

Figure 10. Dimension and location of the redesigned pre-chilled device

The first step in simulation is to pre-chill the mass attached to the bottom before starting gas filling. The change of average temperature of the pre-chilled mass is plotted in Fig 11. The duration of the chilling is 30 minutes and increasing the refrigerant flow rate means lower temperature within a fixed time. For this ideal case with infinite flow rate, the heat sink can be chilled to 0°C in only 5 minutes, this is the shortest time that pre-chilling takes with current inlet conditions in the model.

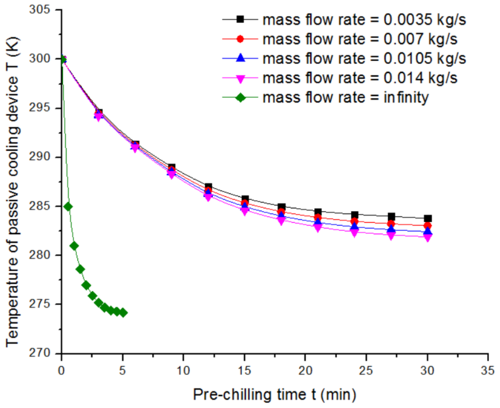

Figure 11. Average temperature of the pre-chilled device vs. pre-chilling time

Second step is to fill the CNG into the cylinder with refrigerant loop stopped. Two pre-chilled cases are presented in Fig. 12. In case (a), the heatsink has been pre-chilled by a refrigerant mass flow rate of 0.0035 kg/s for 30 minutes. Case (b) is pre-chilled by constant boundary temperature for 5 minutes. At the end of the refill, compared with the case without cooling, pre-chilling achieved with constant boundary temperature increases the filled mass by 6.6%, while the number drops to 5% for case (a), for which a refrigerant flow rate of 0.0035kg/s is applied. This indicates that pre-chilling is also an effective way to improve fill efficiency.

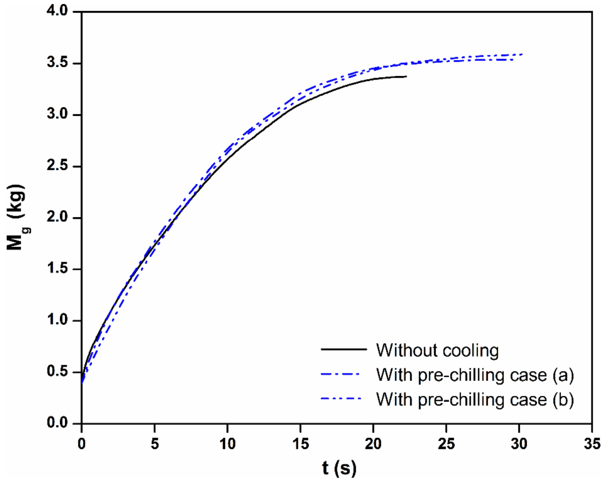

Figure 12. Dynamic change in the mass of gas filled

## V. IMPROVING FILL EFFICIENCY WITH REAL-TIME CHILLING

One disadvantage for pre-chilling is that the total filling time exceeds the fast refill regime. Increasing mass flow rate to a high enough value is a possible way to reduce the time, but mass flow rate can also be restricted by the power of coolant supplying system. A new concept called real-time chilling is proposed to avoid the long pre-chilling time. While the gas inside the cylinder is heated by compression work done by the incoming gas flow, it is possible to utilize the expansion (the Joule–Thomson effect) of another flow of CNG outside the cylinder to cool the gas inside the cylinder. As shown in Fig. 13, there is cavity at the outside of the rear heat sink. Another flow of natural gas only for chilling expands with gas temperature lowered. The low temperature expansion flow removes heat from the gas inside the cylinder actively. This chilling flow starts simultaneously with the filling flow into the cylinder. The low pressure chilling flow coming out of the cavity can be transported to other natural gas systems or re-compressed to the gas reservoir. This concept and related model still need to be investigated as a main future work to verify its effect on efficient fast refill.

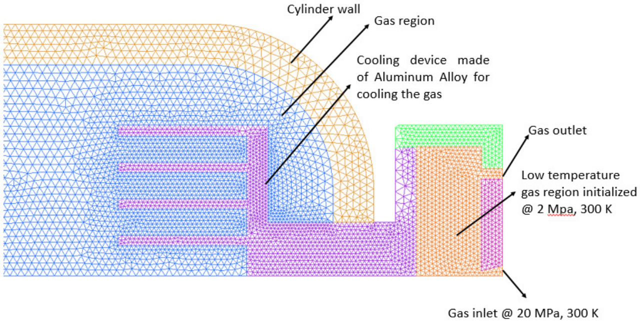

Figure 13. The rear part of the cylinder model for real-time chilling

## VI. CONCLUSION

In this paper, in terms of improving the fill efficiency of CNG fast refill, three different thermal management methods are presented with some research results displayed, giving a whole map of cooling strategies including the effects on the thermal behaviour and fill efficiency of the CNG fast refill process.

Some conclusions can be drawn from the results of research on active cooling and pre-chilling. Both methods can effectively increase the fill efficiency of the fast refill process for CNG. For active cooling, the best improvement that can be achieved with the current design is 7%, which is higher than 4.5% with active cooling conducted at the front part of the cylinder. This location effect indicates that it is better to apply cooling to the rear part of the cylinder. For pre-chilling, time spent and results from this method are dependent on the mass flow rate of supplying refrigerant flow when inlet conditions are fixed. For the ideal case with infinite flow rate, the pre-chilling can achieve a maximum improvement on fill efficiency by 6.6%, which is slightly lower than that of active cooling. Pre-chilling also takes much more time to cool the thermal mass before filling the cylinder, which is less time-economic than active cooling.

Compared with the first two methods researched, the real-time chilling concept can balance the time efficiency and cooling effects. It presents good prospect and need further work to verify this idea. Among the three thermal management concepts discussed in this paper, each of them has its advantages and disadvantages. Proper thermal management method should be chosen based on comprehensive assessment of the compatibility and practicality of each method in a specific scenario.

Current research has provided important guidelines for thermal management on efficient fast refill combining the advantage of acceptable computation time by using 2-D axisymmetric model. In the future, real-time chilling concept will be firstly examined based on current model. After that, as the 2-D model may cause abnormal shape of the coolant loop and the fins of the heat sink, a 3-D model will be built for better realization of the cooling strategies and better understanding of the thermal and flow field. Also, basic experiment will be done to verify certain thermal management concepts.

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