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Exploitation of phase change materials for temperature control during the fast filling of hydrogen cylinders

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ABSTRACT

We investigate the use of phase change materials (PCM) as a means to reduce the temperature rise occurring during fast filling of hydrogen cylinders. The ability to refuel quickly is one of the main factors that can influence the uptake of new automotive energy vectors. The rate at which a hydrogen fuel tank can be filled is limited by heat-up of the cylinder due to compression of the gas inside the cylinder. Slower filling allows more time for heat to dissipate. However it is considered necessary to bring the refuelling time down to between three to five minutes, so called fast filling, for pressurised hydrogen to be a convenient automotive fuel for private vehicles [1]. High temperatures may lead to structural degradation of composite cylinder structures, and the maximum cylinder temperature permitted is set as 358 K by various international standards and regulations [2]. Two types of cylinders are currently used as on-board storage for hydrogen-powered cars: Type III and Type IV. The structure of both cylinders consists an outer laminate, which is made of a carbon fibre reinforced polymer (CFRP) to provide the structural strength and an inner liner whose main purpose is to prevent leakage [3]. The inner liner of the Type III cylinder consists of an aluminium alloy while plastic is used in the Type IV cylinder. The fast filling protocol of light duty hydrogen vehicles is currently established by the SAE TIR J2601 [4] for two pressure classes; namely 35 MPa and 70MPa and three fuel delivery temperatures (233 K, 243 K and 253 K). For a given delivery pressure and temperature, the fill time may be reduced by enhancing the transfer of heat out of the cylinder, or absorbing heat in a heat sink within the cylinder. Use of a heat sink within the cylinder may be advantageous because it does not rely upon rapid heat exchange through the high pressure cylinder, and can limit the peak temperature attained while the heat is dissipated. The heat sink should have a high specific and volumetric heat capacity, making phase change materials attractive, and should be configured in order to achieve a high coefficient of heat transfer with the gas within the cylinder. In this study we have developed and validated an accurate numerical model for fast filling of hydrogen cylinders, including the effect of PCM heat sinks, allowing rapid evaluation of different cylinder specifications and filling strategies. The modelling employs a zonal approach for the properties of the fluid in the cylinder and a one-dimensional description of heat transfer through the cylinder wall. Modelling for convective heat transfer in the cylinder is developed and validated using experimental data [5] and computational fluid dynamics simulations results across a range of filling conditions and cylinder geometries. Modelling for the mass inflow into the cylinder is developed including effects of the real-gas effects on the flow through the entry nozzle. The one-dimensional model has been validated against different published test cases and has shown a reasonable accuracy in

determining the rise in the gas temperature profile for the fast filling of both Types III and IV hydrogen cylinders, for different fill times, while lowering the computational time by a factor of approximately six thousand compared to computational fluid dynamics simulations.

A case study is performed for the fast filling of a hydrogen vehicle (Toyota Mirai [6]) that consists of two 70 MPa cylinders with volumes of 60.0 L and 62.4 L. The simulations in the one-dimensional model at an ambient temperature of 293 K show that pre-cooling is required to keep the gas temperature below the 358 K for the filling of the cylinders within three minutes (Figure 1). The pre-cooling temperature is incrementally increased by 10 K from its lowest stated value of 233 K from the SAE TIR J2601 hydrogen filling protocol and at the ambient temperature of 293 K; the three minute fill requires pre-cooling of the gas to 253 K or lower (Figure 1). A decrease in fill time can be obtained by increasing the rate at which gas is delivered into the cylinder and lowering the pre-cooling temperature of the gas (Figure 2). The inclusion of a 2 mm layer of a PCM that consists of graphite particles dispersed in paraffin wax [7] in between the liner and laminate of the cylinders show that less pre-cooling is required over the range of fill times and ambient temperatures (Figure 2).

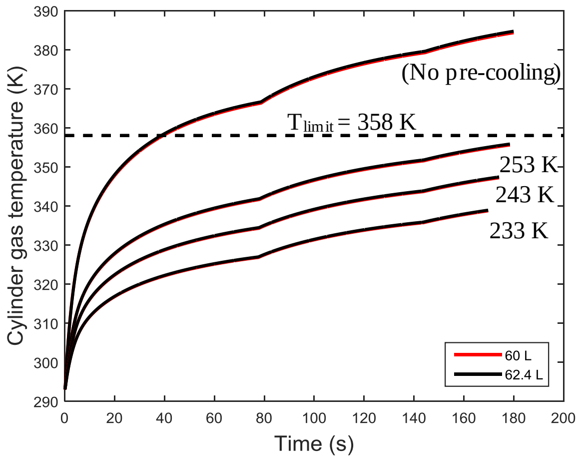

Figure 1: Comparison of the gas temperature profile with the delivery pressure set to 28.5 MPa/min for pre-cooling temperatures of 233 K, 243 K and 253 K and without pre-cooling (Ambient temperature = 293 K).

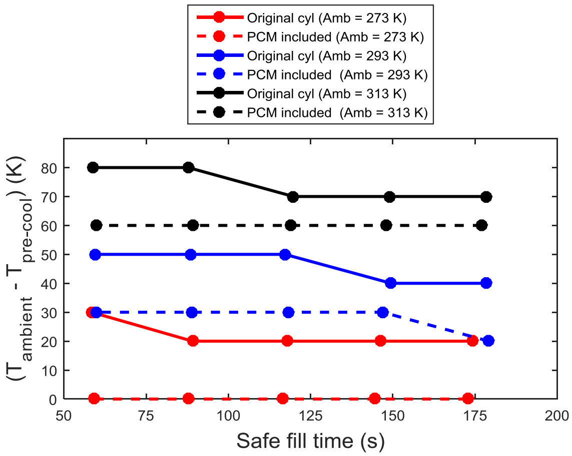

Figure 2: Comparison of the amount of pre-cooling required at ambient temperatures of 273 K, 293 K and 313 K for different fill times for the original cylinder and the cylinder that includes the PCM.

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