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Numerical Simulation of Fast Filling of a Hydrogen Tank

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ABSTRACT

High pressure gas is a widely used storage mode for hydrogen fuel. A typical hydrogen tank that is charged with hydrogen gas can function as a hydrogen supply source in a large number of applications. The filling process of a high pressure hydrogen tank should be reasonably short. However, when the fill time is short, the maximum temperature in the tank increases. Therefore the process should be designed in such a way to avoid high temperatures in the tank because of safety reasons. The paper simulates the fast filling process of hydrogen tanks using Computational Fluid Dynamics method. The local temperature distribution in the tank is obtained. Results obtained are compared with available experimental data. Further work is going on to improve the accuracy of the calculations.

Key Words: Hydrogen energy, Compressed hydrogen gas, Fast filling, Tank filling

1. INTRODUCTION

Hydrogen is one of the most abundant elements on the earth and offers an alternative as a source of energy that is at once clean, flexible, and secure. It is also environment friendly because it burns without producing carbon dioxide. The principal attraction of hydrogen as a possible energy source for the aviation and automotive industry is that it stores nearly three times the energy per unit mass as fossil fuels like gasoline. However, physical characteristics of hydrogen make it difficult to store in large quantities without taking up large amount of space. Development of compact, reliable and safe storage technology is one of the most important barriers to be overcome for hydrogen to gain acceptance as a major source of energy. Operating requirements for effective hydrogen storage for transportation include; appropriate thermodynamics, quick uptake and release of fuel, high storage capacity, effective heat transfer, light in weight and conservative in space, long cycle lifetime for hydrogen absorption/desorption, high mechanical strength and durability, and safety under normal use and acceptable risk levels under abnormal conditions.

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storage. For successful adaptation in propulsion systems, the fuel tank should be light in weight and strong enough to withstand the high pressures. Therefore the hydrogen fuel tanks are usually made of Fiber Reinforced Plastic composites to reduce the weight in combination with metal or polymer liners. Purpose of the liner is to provide a gas tight seal while the outer laminate provides the structural integrity to the tank.

During the filling of the tank, the temperature of the gas increases because of two reasons: (1) the negative Joule Thomson coefficient for hydrogen at the pressure and temperature of filling and (2) heat of compression within the cylinder. Previous studies on hydrogen gas behavior have revealed that the effect of the former is insignificant while considering the thermodynamics of the entire process. ISO 15869 [1] stipulates that the gas temperature should not exceed 85°C during the fast filling process. Also the maximum pressure of filling should be 125% of the rated pressure of the tank. The increase in temperature due to the compression of gas, the necessity of meeting the safety stipulation and the cooling of the gas once the fill process is completed may all contribute to the under filling of the tank which is undesirable. This necessitates the need for a prior understanding of the behavior of the hydrogen gas within the tank during the filling process.

The objective of the present study is to numerically simulate the temperature field within a compressed hydrogen gas cylinder during filling, in order to determine the temperature variations of the hydrogen gas within the tank and enable density calculations based on pressure and temperature. This will aid in formulating an optimum filling strategy which is efficient and safe. Numerical results obtained were compared with available experimental results and numerically simulated data.

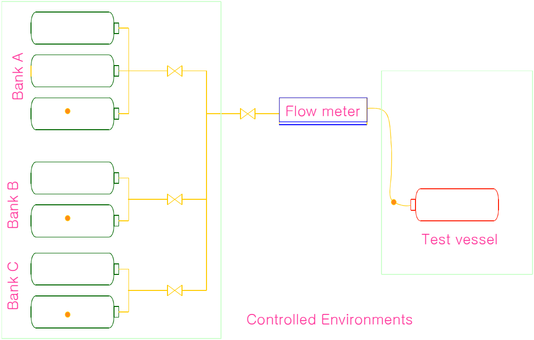

Fig. 1 Typical hydrogen gas filling unit (2)

2. NUMERICAL SIMULATION

Computational Fluid Dynamics simulations were carried out under conditions that replicate the experimental investigations of fast filling of a compressed hydrogen tank. Flow was treated as compressible, viscous, unsteady and turbulent. Commercial software Fluent 6.3 is used for the computations. The axisymmetric, time dependent Navier Stokes equations, with the two equation standard k-ε turbulent model were used in the computation. Governing equations are discretized spatially with a finite volume scheme. For time derivatives, an implicit time stepping scheme is used.

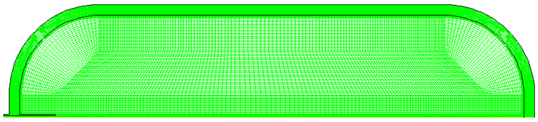

Fig. 2 Computational grid

Computational domain used for simulating the filling process is illustrated in Fig. 1. Mesh was generated in the GAMBIT and read into FLUENT. A structured mesh was employed in computations. Grids were densely clustered in near wall regions to capture the flow features in boundary layers. Axisymmetric geometry is considered since the effects of gravitational and buoyant forces may be assumed negligible during the fast filling. However, it is to be noted that the assumption no longer holds good once the filling process is over and the gas begins to settle in the tank or the filling process is slow. The model is divided into two domains: the fluid domain filled with hydrogen gas and the solid domain involving the liner and the laminate regions on the tank wall and the inlet tube. Liner and laminate regions are assumed to be isotropic.

Total pressure boundary condition is used at the inlet. The inlet pressure is varied with time as per available experimental data. The inlet total temperature is also varied with time as per the experimental inlet conditions during the fast filling process. No slip condition is used at the tank inside wall to solve mass, momentum and the turbulent quantities. Ideal gas equation of state is used in the density computation. Energy equation for the gas is coupled to the energy equation for the walls. A constant value for the convective heat transfer coefficient is specified at the outer wall. Radiation heat transfer between the ags and the walls is assumed to be negligible. Since filling process is very fast, the ambient temperature is also assumed to be constant during the process. Grid independence of solutions was checked. Solution convergence was decided by observing the mass flow rate of gas entering the tank and the mass averaged temperature of the gas within the cylinder. The initial pressure and temperature of the gas are assumed to be uniform with values 9.9MPa and 293.4K respectively. The wall temperature is assumed to be same as the gas temperature.

Table 1 Material Properties for Tank Wall

	Material	Specific Heat	Thermal Conductivity	Density
		(J/kg/K)	(W/mK)	(kg/m^3)
Liner	Aluminum	2730	167	900
Laminate	CFRP	1494	1	938

3. RESULTS AND DISCUSSION

Experimental results of Dicken and Merida [3, 4] were used to simulate the current numerical model. Pressure and temperature changes at the inlet of the tank reported in their paper are used in the current investigation. The experimental data were available for a fill time of 40s. The numerical study considered the same inlet conditions and duration for the filling simulation. The main objective of the work was to obtain the temperature field and observe the flow pattern within the tank during filling. The temperature distributions within the tank during various time intervals during the fill are illustrated in a series of figures from 3 to 10.

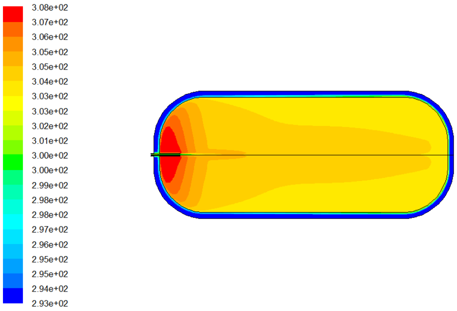

Fig. 3 Temperature distribution after 5 second

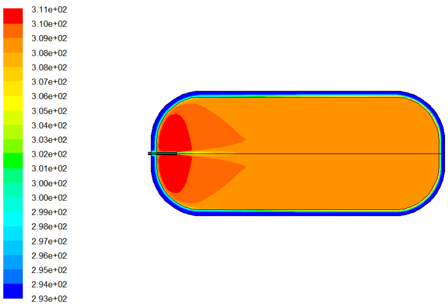

Fig. 4 Temperature distribution after 10 second

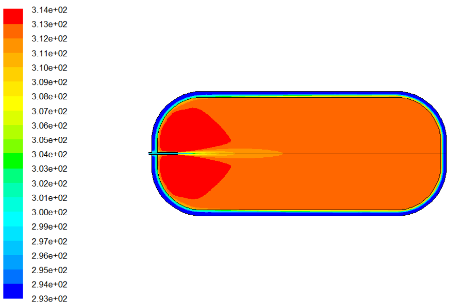

Fig. 5 Temperature distribution after 15 second

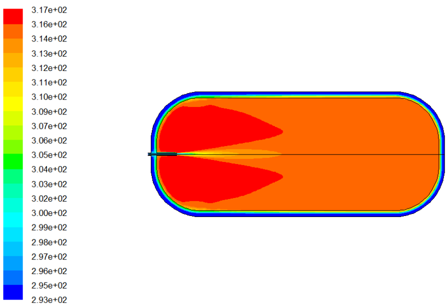

Fig. 6 Temperature distribution after 20 second

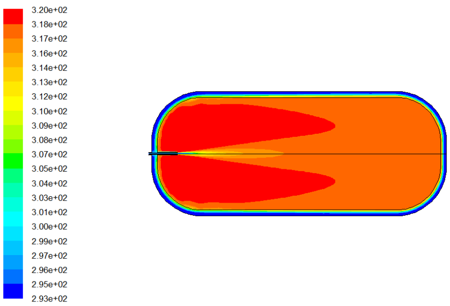

Fig. 7 Temperature distribution after 25 second

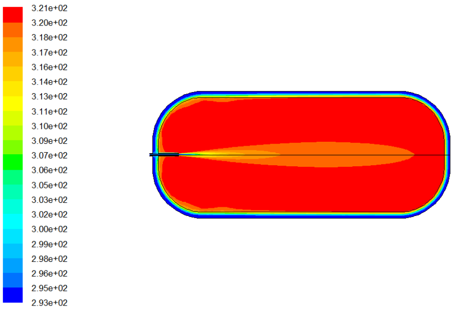

Fig. 8: Temperature distribution after 30 second

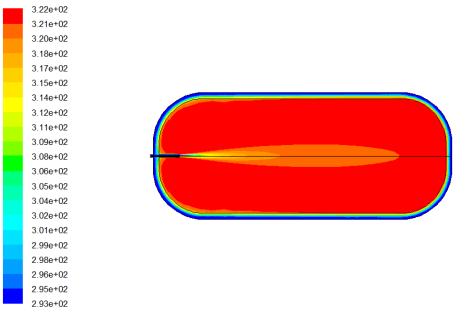

Fig. 9: Temperature distribution after 35 second

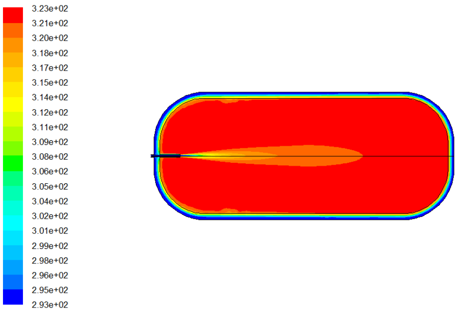

Fig. 10: Temperature distribution at the end of the fill

The present computations have captured the pattern of temperature increase and the temperature distribution within the tank. The highest temperature region is located in the vicinity of the inlet tube. The incoming gas is at a much lower temperature than the gas inside the tank. Hence a large temperature gradient exists in the near inlet region. The temperature of the bulk gas region is more or less uniform. There is only negligible change in the temperature of the laminate section of the wall.

Figure 11 shows the velocity vectors of the gas within the tank towards the end of the fill. It gives an idea about the flow pattern within the tank including the regions of vortex flow. The inlet jet of gas is found to strike at the bottom of the tank. This may cause an increase in temperature in this region.

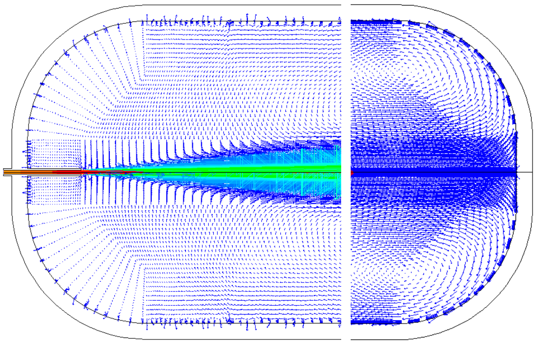

Fig. 11 Velocity vectors at time nearly the end of the fill

Figure 12 shows the radial temperature profiles. There is a significant temperature gradient in the vicinity of the inlet tube. The wall temperatures also show a variation in a similar pattern. There is an increase in the centerline temperature from the inlet to the bottom of the tank as shown in figure 13.

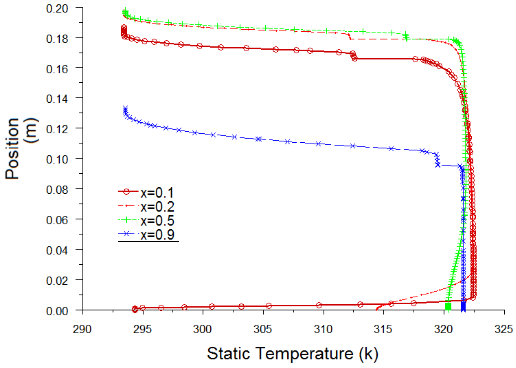

Fig. 12 Radial temperature distribution at different locations along the axis at the end of the fill

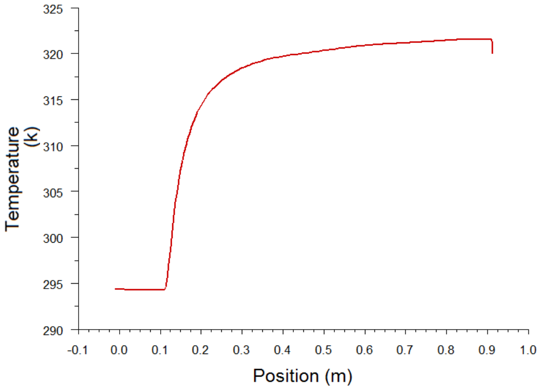

Fig. 13 Temperature along the axis at the end of the fill

The results of the numerical computations are compared with the previous computational and experimental results in figure 14. It shows the mean temperature of the fill for the three cases, namely experimental results, real gas simulation and ideal gas simulation. The difference in the mean temperature of the gas is because of the difference in initial conditions considered.

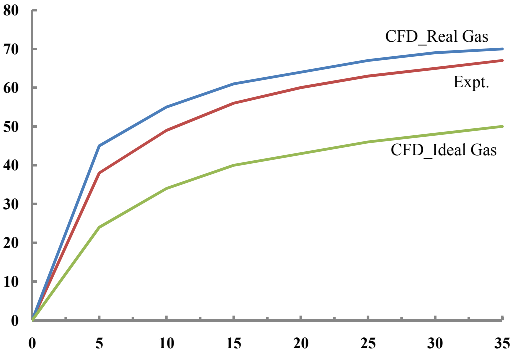

Fig. 14 Mean Temperature during the fill

4. CONCLUSION

Computational studies were carried to investigate temperature field within a compressed hydrogen gas tank during the fast filling process. Axisymmetric, unsteady, compressible Navier Stokes equations have been solved numerically to simulate the flow field. The computational results have predicted the temperature field with reasonable accuracy. A more accurate prediction of the temperature distribution warrants the inclusion of real gas effects. Further work is going on to incorporate the real gas effects.

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