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Modeling thermal response of polymer composite hydrogen cylinders subjected to external fires

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A B S T R A C T

With the anticipated introduction of hydrogen fuel cell vehicles to the market, there is an increasing need to address the fire resistance of hydrogen cylinders for onboard storage. Sufficient fire resistance is essential to ensure safe evacuation in the event of car fire accidents. The authors have developed a Finite Element (FE) model for predicting the thermal response of composite hydrogen cylinders within the frame of the open source FE code Elmer. The model accounts for the decomposition of the polymer matrix and effects of volatile gas transport in the composite. Model comparison with experimental data has been conducted using a classical one-dimensional test case of polymer composite subjected to fire. The validated model was then used to analyze a type-4 hydrogen cylinder subjected to an engulfing external propane fire, mimicking a published cylinder fire experiment. The external flame is modelled and simulated using the open source code FireFOAM. A simplified failure criteria based on internal pressure increase is subsequently used to determine the cylinder fire resistance.

Introduction

In the pursuit of zero carbon emission from power generation, hydrogen has been recognized as a promising energy carrier and is being increasingly used in a variety of applications. One of the prominent examples of hydrogen utilization is in fuel cells for automotive power generation. Hydrogen fuel cell vehicles (HFCV) are currently being developed by a number of car manufacturers. They are expected to be commercialized in the near future.

The commercialisation of HFCVs requires onboard storage of hydrogen at sufficient quantity to cover reasonable driving distances. While different storage techniques are under development, the only commercially available technology stores compressed hydrogen at 35–70 MPa in a cylinder tank typically made of Carbon-Fiber-Reinforced Polymer (CFRP). One of the important aspects in the design of cylinder tanks is their fire resistance. In the probable event of HFCV fire accidents, the tank must be strong enough to withstand the thermomechanical loading arising from an external fire. According to the regulation, the tank must also be equipped with Temperature-activated Pressured Release Device (TPRD), which will vent the hydrogen from the tank whenever a peculiarly high temperature corresponding to the fire is detected. A sufficient tank fire resistance would mean that the venting of hydrogen can proceed slowly, such that there will be no overpressure in the case of no ignition, or if a flame does ignite, it will not be harmful to the surrounding people or objects in terms of length and heat radiation [1].

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Unfortunately, the fire resistance of current generations of hydrogen tanks is only around 12 min for type 3 cylinders (with aluminium liner) [2], and 3.5–6.5 min for type 4 cylinders (with plastic liner) [3]. Such fire resistance is still unacceptable to allow for a timely evacuation by fire brigades or first responders. For comparison, venting of 35 MPa hydrogen gas through a 5 mm TPRD orifice within 3 min corresponds with a flow rate of about 390 g/s that causes an overpressure of 10–20 kPa within 2 s [4]. This is high enough to destroy a residential garage. Under the same venting condition at 70 MPa in an open space, the safety distance would be about 50 m, which is intolerable to the public. Accordingly, enhanced fire resistance of onboard hydrogen cylinder tanks is urgently needed.

A number of previous studies have attempted to address the characteristics of polymer composite and/or CFRP material subjected to external fires, both for general purpose and onboard hydrogen storage applications. The use of computational modelling and simulation is commonplace in these studies. The thermal response of polymer composite for general application has been extensively modelled [5–9], taking into account a number of important physical and chemical aspects, such as thermal decomposition reaction of the CFRP, the transport of volatile gas towards the heated surface, pressure rise in the CFRP, and thermal expansion/contraction. For onboard hydrogen storage application, numerical models have been employed to study the hydrogen cylinder behaviour subjected to both engulfing fire [10,11] and localized fire [12–14].

Of the above numerical studies on thermal response of hydrogen storage cylinders, none has incorporated the prediction of cylinder fire resistance into the coupled model of external fire and cylinder thermal field simulations. Coupling of fire simulation and cylinder simulation has actually been reported [10,13,14], but the model did not predict the fire resistance. Moreover, the cylinder thermal model only considered pure conductive heat transfer, without effects of resin decomposition and volatile gas transport.

In this paper, thermal response prediction of a type-4 CFRP hydrogen cylinder subjected to engulfing external propane fires, mimicking a published hydrogen tank fire exposure burst experiment [3], is presented. The initial internal pressure is 34.3 MPa. The simulation of the cylinder thermal field is carried out using the open source Finite Element (FE) code Elmer [15], taking into account the CFRP resin decomposition and volatile gas transport. The thermal loading from the external flame is represented as heat flux predicted in a separate simulation of propane pool fire using CFD code FireFOAM [16]. The predicted thermal response, in conjunction with a simplified failure criteria, is subsequently analyzed in order to determine the fire resistance of the cylinder.

Numerical models

The numerical simulations in this paper employ two mathematical models. The first model is a Finite Element model to simulate the thermal response of the hydrogen cylinder, and the second model is a Finite Volume CFD model for predicting external fire impinging on the cylinder wall. At this stage, several assumptions and simplifications are made. The fire loading on the cylinder is represented by a constant heat flux based on the predicted mean heat flux obtained from CFD simulation.

Finite Element model for hydrogen cylinder thermal response

The thermal process in the heating of CFRP cylinder by external fire is initially dominated by heat transfer in the form of heat conduction. After the temperature reaches a certain threshold, decomposition reaction starts to take place. At the onset of decomposition, heat may be absorbed or released from the reacting CFRP resin and fibers. As the heating proceeds, the composite degrades to form gaseous products, which are convectively transported away towards the heated surface. The corresponding thermal model thus incorporates these three important ingredients, i.e. heat conduction, decomposition, and volatile gas convection. The governing equation in the model is expressed as follows:

$$\rho C_p\left(\frac{\partial T}{\partial t}\right) - \nabla\cdot(k\nabla T) = -\dot{m}_g C_{p,g}\frac{\partial T}{\partial x} + \frac{\partial \rho}{\partial t}\left(Q_{dec} - h_c + h_g\right) \quad (1)$$

In the above equation, ρ is the CFRP density, C_p CFRP specific heat, T temperature, k thermal conductivity, $\dot{m}_g$ the gas mass flux, $C_{p,g}$ the specific heat of volatile gas, Q_{dec} the heat of decomposition, h_c the composite enthalpy, and h_g the gas enthalpy. The gas mass flux in the first source term on the right hand side of the above equation can be formulated as:

$$\dot{m}_g = \int_l^x \frac{\partial \rho}{\partial t} dx \quad (2)$$

The parameter $\frac{\partial \rho}{\partial t}$, the time rate of change of decomposition, is generally expressed as an nth-order kinetic rate equation of Arrhenius form, as follows:

$$\frac{\partial \rho}{\partial t} = -A\rho\left(\frac{m - m_f}{m_0}\right)^n \exp\left(\frac{-E_a}{RT}\right) \quad (3)$$

where A is the pre-exponential factor, m mass, m_0 initial mass, m_f final mass, E_a activation energy, and R gas constant.

The composite enthalpy is formulated as:

$$h_c = \int_{T_0}^{T} C_p dT \quad (4)$$

and the gas enthalpy is expressed as:

$$h_g = \int_{T_0}^{T} C_{p,g} dT \quad (5)$$

CFD model for external fire simulation

A Finite-Volume-based CFD model is used to simulate the external propane fire. The model [17] employs the extended Eddy Dissipation Concept (EDC) combustion model within the frame of Large Eddy Simulation (LES) to deal with turbulence [18,19]. This model has been developed and implemented in the dedicated fire simulation solver FireFOAM, within the open source CFD code OpenFOAM.

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