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Pre-Cooling Strategies for the Refueling of Hydrogen Cylinders in Vehicular Transport

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Abstract : Hydrocarbon-based fuel vehicles are a major contributor to air pollution due to harmful emissions produced, leading to a demand for cleaner fuel types. A leader in this pursuit is hydrogen, with its application in vehicles producing zero harmful emissions and the only by-product being water. To compete with the performance of conventional vehicles, hydrogen gas must be stored on-board of vehicles in cylinders at high pressures (35–70 MPa) and have a short refueling duration (approximately 3 mins). However, the fast-filling of hydrogen cylinders causes a significant rise in temperature due to the combination of the negative Joule-Thompson effect and the compression of the gas. This can lead to structural failure and therefore, a maximum allowable internal temperature of 85°C has been imposed by the International Standards Organization. The technological solution to tackle the issue of rapid temperature rise during the refueling process is to decrease the temperature of the gas entering the cylinder. Pre-cooling of the gas uses a heat exchanger and requires energy for its operation. Thus, it is imperative to determine the least amount of energy input that is required to lower the gas temperature for cost savings. A validated universal thermodynamic model is used to identify an energy-efficient pre-cooling strategy. The model requires negligible computational time and is applied to previously validated experimental cases to optimize pre-cooling requirements. The pre-cooling characteristics include the location within the refueling timeline and its duration. A constant pressure-ramp rate is imposed to eliminate the effects of rapid changes in mass flow rate. A pre-cooled gas temperature of -40°C is applied, which is the lowest allowable temperature. The heat exchanger is assumed to be ideal with no energy losses. The refueling of the cylinders is modeled with the pre-cooling split in ten percent time intervals. Furthermore, varying burst durations are applied in both the early and late stages of the refueling procedure. The model shows that pre-cooling in the later stages of the refuelling process is more energy-efficient than early pre-cooling. In addition, the efficiency of pre-cooling towards the end of the refueling process is independent of the pressure profile at the inlet. This leads to the hypothesis that pre-cooled gas should be applied as late as possible in the refueling timeline and at very low temperatures. The model had shown a 31% reduction in energy demand whilst achieving the same final gas temperature for a refueling scenario when pre-cooling was applied towards the end of the process. The identification of the most energy-efficient refueling approaches whilst adhering to the safety guidelines is imperative to reducing the operating cost of hydrogen refueling stations. Heat exchangers are energy-intensive and thus, reducing the energy requirement would lead to cost reduction. This investigation shows that pre-cooling should be applied as late as possible and for short durations.

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