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Design of a novel and efficient hydrogen compressor for wind energy based storage systems

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ABSTRACT

In a hybrid wind power system, the excess wind energy is stored in the form of compressed hydrogen. Wind turbine generates electricity from the wind. The excess power (after meeting the load requirements) is used to generate hydrogen using an electrolyzer. The generated hydrogen is compressed using a compressor and sent to storage in a high pressure storage tank. The compressor should be operated at near isothermal conditions to reduce the power consumed by the compressor, thereby increasing the efficiency of the system. This paper deals with CFD modeling of a novel water spray cooled reciprocating hydrogen compressor which provides efficient cooling of the system during compression. Water is sprayed directly into the compressor cylinder during the compression stage. The water spray breaks into droplets, which provides large surface area to absorb the heat of compression thereby reducing the temperature. The heat capacity of water being order of magnitudes higher than that of hydrogen provides efficient cooling of the compressed gas with small water to hydrogen volumetric ratio. The concept of water spray cooling during compression is demonstrated through a three dimensional computational fluid dynamics (CFD) simulation.

Introduction

Wind energy is an important source of renewable energy. Wind energy being an intermittent source of energy, it is important to store the wind energy to increase its penetration. Of the different storage options, storing excess wind energy in the form of hydrogen is feasible option as in the case of the Ramea island [22]. The excess wind energy in the form of electrical energy is diverted to the electrolyzer to generate hydrogen. The hydrogen generated can be stored either as compressed hydrogen [24], as liquid hydrogen [2], as cryo-compressed hydrogen [1], in cryo-adsorbers [3], in metal hydrides [15] and in chemical hydrides [7]. Of these different hydrogen storage options, compressed hydrogen storage is the simplest without much infrastructure. A compressor is used to compress the hydrogen generated from the electrolyzer and is stored in a high pressure storage tank [14].

In the case of compressed hydrogen storage system, the operation of a compressor plays an important role in the efficiency of the storage system. Since, hydrogen production is intermittent, continuous operation of the compressor is not recommended as it will lower its efficiency and the life span of the compressor. Raju and Khaitan, 2012 [14] have proposed intermittent operation of the compressor as and when required. The hydrogen from the electrolyzer is temporarily

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stored in a buffer space. The compressor will operate when the buffer pressure exceeds a certain level. When the compressor is in operation, the buffer pressure will gradually drop. Compressor will stop when the pressure in the buffer drops to a certain cut-off level. This intermittent operation increases the efficiency of the system provided the compressor can operate intermittently without degrading its performance.

The compressor has to be operated under near isothermal conditions to reduce the amount of work done for the compression process. There are several ways of achieving it. The most common procedure is to perform compression in multistage and use intercoolers between the compression stages to cool the gases followed by an after-cooler. Another efficient alternative is to use water spray directly into a reciprocating compressor [5,9]. The advantage of water spray cooled compressor is that near isothermal compression can be achieved in a minimal number of stages without any need for intercoolers. This procedure has been proven to achieve good compression ratio even in single stage compression with near isothermal operating conditions [11].

Although the concept of water spray cooled compressor existed for quite some time, there is not much effort in modeling a water spray cooled compressor. The modeling of water spray compressor is quite complex (presence of spray droplets, moving boundaries, requirement of local mesh refinement for adequately resolving the flow field etc.). The atomization of spray is extremely complex involving transient two-phase, turbulent flows at high pressures, with a wide range of temporal and spatial scales [21]. There are 2 broad approaches to model the spray atomization. First approach uses Eulerian–Lagrangian approach in which gas phase is solved using Eulerian approach and the dispersed phase is solved using a Lagrangian approach where individual droplet parcels are tracked [12,13]. The second approach uses Eulerian–Eulerian two-phase methodology [4], treating different size classes of droplets as separate and inter-penetrating phases. However, the second approach is computationally very expensive and hence the first approach is typically used. Coney et al., 2002 [11] provide CFD modeling of water spray cooled compressor using StarCD. However, they do not provide much detail about their CFD model. This paper deals with preliminary investigation of a novel water spray based compressor for hydrogen systems using CFD simulations to demonstrate the physics behind water spray cooling of a hydrogen compressor.

Description of spray cooled hydrogen compressor

Water spray cooled hydrogen compressor consists of a cylinder with a reciprocating piston which compresses the hydrogen gas. During the compression stage, water is sprayed from the spray injectors located on the head of the compressor. The water spray will break into several minute droplets, thereby increasing the surface area of the droplets. The large surface area of the droplets is in direct contact with the hot gas, thereby facilitating heat transfer from the hot gas to the droplets. Note that the heat capacity of water is roughly around 4000 times that of hydrogen (density of water is ~10,000 times higher than that of hydrogen at 300 K and 1 bar pressure and specific heat capacity (c_v) of water is ~0.4 times of that of hydrogen at 300 K and 1 bar pressure). This allows the droplets to cool the hydrogen gas significantly with only a slight increase in the water droplet temperature. Effectively most of the heat transfer is provided by the sensible heat of water. Droplet evaporation would also be present which provides additional cooling in the form of latent heat of vaporization of water.

The compressor is a two stroke compressor. During the intake (or expansion) stroke, the intake valve opens. The piston moves from top dead center (TDC) to bottom dead center (BDC). In this study, 0° CA (crank angle) refers to TDC and −180° CA refers to BDC. During intake stroke, hydrogen from the buffer is sucked into the cylinder. The intake valve closes when the piston reaches BDC. During the compression stroke (BDC to TDC), the hydrogen gas in the cylinder is compressed. Water spray is injected into the compressor, which facilitates the cooling of the compressed gas. The exhaust value open before the piston reaches TDC and the compressed hydrogen gas is discharged along with the spray droplets. The water droplets are separated out in the discharged section before the compressed hydrogen is stored in a high pressure tank. Note that the compressed hydrogen will still contain moisture due to evaporation of the droplets. The separated water is hot and is stored in a hot water tank. This water can be used for other purposes as per the local heating needs. The stored hydrogen can be reused later to generate electricity either by using a fuel cell or by using a hydrogen combustor.

Physical properties of hydrogen

Note that hydrogen gas deviates from ideal gas behavior at high pressures and temperatures [10]. Thus, it is important to include the real gas effects. Redlich-Kwong [18] equation of state is used in this study.

$$Pv = Z\left(\frac{R}{W_g}\right)RT \tag{1}$$

$$Z = \frac{v_r}{v_r - 0.08664} - \frac{0.42748}{(v_r + 0.08664)T_r^{3/2}} \tag{2}$$

where P is the pressure, T is the temperature, Z is the compressibility factor, W_g is the molecular weight of hydrogen gas, R is the universal gas constant, $v_r = Pv/RT_c$ is the reduced specific volume, $T_r = T/T_c$ is the reduced temperature, T_c is the critical temperature, P_c is the critical pressure and v is the specific volume of the gas. For hydrogen gas, the critical temperature is 33 K and the critical pressure is 1.3e6 Pa.

The diffusion of water vapor D in hydrogen [23] is given as

$$D = D_o\left(\frac{T}{273.0}\right)^n \tag{3}$$

where D_o is the diffusion of water vapor in hydrogen gas at 273 K (7.34e-5 m^2/s) and n is temperature dependent exponent (1.84).

The temperature dependent physical properties like specific heat, thermal conductivity, dynamic viscosity etc. are taken from NIST database [10].