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Experimental investigation on -water injected twin screw compressor for fuel cell humidification

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Abstract:

A water injection in Twin Screw compressors was examined in order to develop effective humidification and cooling schemes for fuel cell stacks as well as cooling for compressors. The temperature and the relative humidity of the air at suction and exhaust of the compressor were monitored under constant pressure and water injection rate and at variable compressor's operating speeds. The experimental results showed that the relative humidity of the outlet air was increased by the water injection. The injection tends to have more effect on humidity at low operating speeds/ mass flow rates. Further humidification can be achieved at higher speeds as higher evaporation rate becomes available. It was also found that the rate of power produced by the fuel cell stack was higher than the rate used to run the compressor for the same amount of air supplied. The efficiency of the Balance-Of-Plant (BOP) was therefore higher when more air is delivered to the stack. However, this increase in the air supply needs additional subsystems for further humidification/ cooling of the BOP system.

Keywords

Fuel cell stack, Twin Screw compressor, air supply, water injection, humidity, temperature, Balance-Of-Plant, power

1. Background

Hydrogen fuel cells tend to be the long-term solution to tackle the current environmental threats and future fuel sustainability. They are clean; quite and highly efficient energy sources with great design flexibility and fuel reliability. They encompass broad spectrum of applications ranging from low power electronic devices such as mobile phones and laptops to medium and high power systems including automotive and power generation plants. Despite these attractive advantages, fuel cells still suffer from high cost and the absence of hydrogen infrastructure. These two obstacles are considered to be the major challenge for their market penetration and success. Great efforts were made in recent years to improve the current design of fuel cell systems particularly in terms of cost, volumetric efficiency durability, and also to promote the transition to an established hydrogen economy.

In order to perform the electrochemical reaction of fuel cells, both hydrogen fuel and air/oxygen have to be supplied to the anode and cathode side of the stack respectively. Typical hydrogen supply system comprises of high pressure storage tank, pumps, regulators, and in some designs injectors. The design of air-system is often more complex. Additional air-supply and conditioning sub-systems are needed to deliver the ambient air to the stack as well as to maintain the humidity and temperature of the inlet air at desirable level for optimum fuel cell operation. The amount of air entering the stack is directly proportional to the power produced by the individual cells as described in Equation 1 [1]:

$$\text{Air Usage} = 3.57 \times 10^{-7} \times \lambda \times \frac{P}{V_c} \ \text{kg.s}^{-1} \qquad [1]$$

where λ is stoichiometry, P is the cell power (Watt), and V_c is the cell voltage (V)

In practise, the stoichiometric inlet flow is often made higher than the flow required by the reaction rate in order to remove excessive water from the cathode channels and to avoid flooding phenomenon. Number of air-supply systems including fans, blower and compressors are used for different fuel cell stack designs. Each system is selected to match particular stack requirements with minimum power consumption in order to keep the overall system efficiency, or so-called the Balance-Of-Plant (BOP), optimum. Figure 1 shows a range of air systems that are used in different fuel cell applications. The air-mass flow rate is calculated from Eq.1 assuming $\lambda = 2$ and $V_c = 0.6V$ as typical cell values.

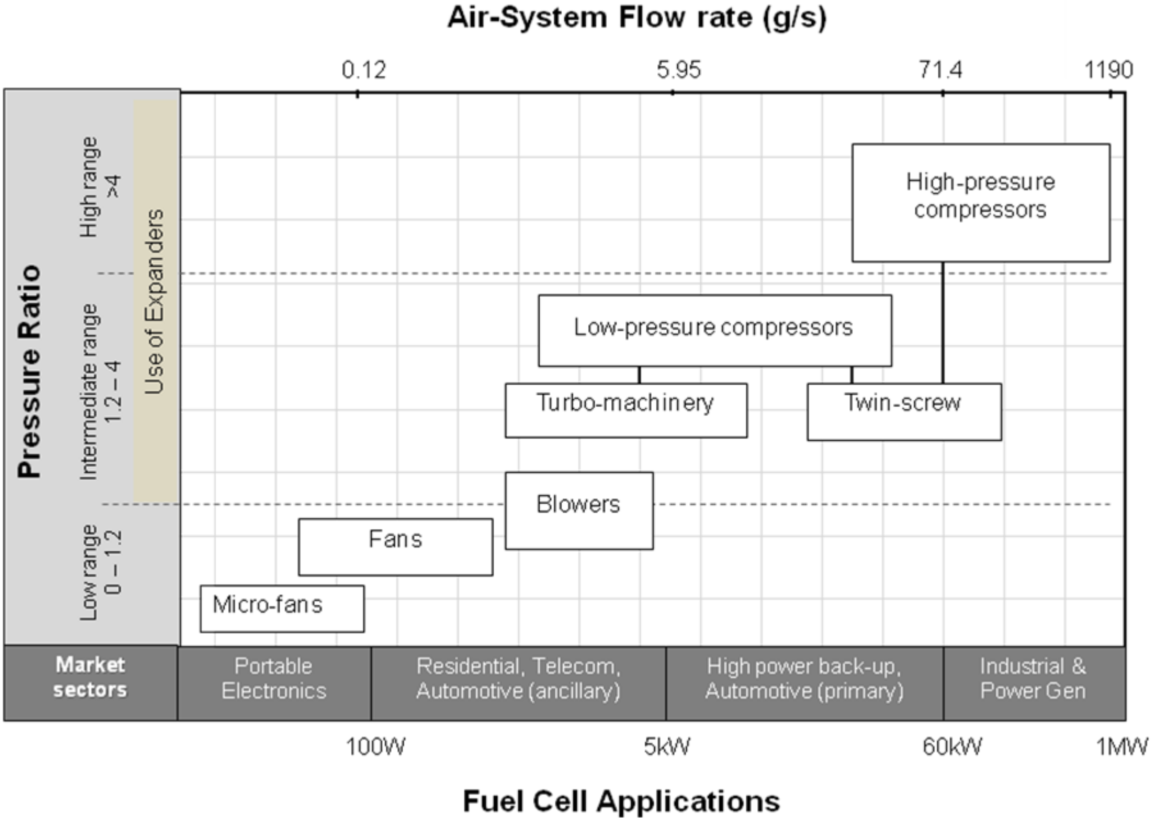

Figure 1 Air-supply systems for different fuel cell applications

Figure 1 indicates that for low fuel cell power range, fans and blowers are more suitable than compressors since they supply enough air to the stack while being compact and require less power to operate. The use of compressors becomes feasible in high power applications particularly for larger systems that require substantial amount of air at high pressures. In the intermediate power region, fans and blowers struggle to supply sufficient air to the stack at reasonable operating pressures whereas compressors become inefficient at low mass flow rates due to considerable internal losses [2]. Low pressure compressors such as turbo-machinery and miniature twin-screw types are therefore expected to play dominant role in that region.

The air supplied to fuel cell stacks needs pre-conditioning before entering the reaction channels of the cells. This is often the case in large air-systems when the temperature of the outlet air exceeds the operating limit of the stack. Humidity and temperature of the inlet air must be kept at desirable levels to achieve optimum fuel cell performance. These two parameters influence the polarization behaviour and the water management of the cell. Increasing the air humidity improves significantly the electrode reaction and conductivity of the membrane [3] and affects the water flooding phenomenon of the cell [4]. Similarly, the increase in temperature causes reduction in the internal resistance as well as in the electrochemical activation loss of the cell [5].

There are different approaches to humidify the reactant air. Humidification can be made internally or externally to fuel cell stacks. Internal humidification could be rather difficult since it adds complexity to stack's design and may cause instability to the water management of the cell. In contrast, external humidification offers more flexibility and better use at high temperatures [6]. In external humidification scheme, two methods are commonly used to humidify the air. These two methods are known as (a) bubble humidification and (b) direct steam injection. Bubble humidification, where the air is finely bubbled through heated water column, is characterised by its simplicity, bulkiness, and the ability to control RH [7] whereas direct steam injection is compact and more complex in design [8]. The choice of one method over the other is determined by the type of application used for, particularly in terms of space availability and the gain in stack's power by implementing that method. For example in automotive applications, where fuel cell stacks have high power capacity, direct steam injection is preferred. The power consumed to humidify the air is still relatively low compared to the gain in the overall stack power.

Another method to humidify the air is by direct water injection. As the name suggests, water is injected directly into the air stream in the form of micro-droplets or mist. Although this method may not provide high level of humidity as steam-based humidification e.g. bubble type or steam injection, but it eliminates the need for heater in the design. The heat produced by the air-supply system can be harnessed and used to evaporate part of the injected water to raise the humidity of the air. In this way, the humidification system becomes more compact with minimum energy requirements.

Previous studies investigated a number of issues concerning compressor designs and systems integration in order to develop advance air management system for fuel cell stacks. The experimental work in [9] showed that using different materials for the scroll part in scroll compressors does not affect the air delivery trend but the benefit rather results in lowering the compressor power consumption due to minimum friction coefficient. The influence of inlet swirl-generator device (SGD) blades position on the compressor performance was examined in [10] to provide better understanding of the SGD impact on the turbocharger behaviour. The interaction of air supply with the fuel cell stack was addressed in [11] and [12]. The simulations in [12] were carried out, using model predictive control (MPC) technique, to control the oxygen excess ratio; whereas the experimental results in [11] highlighted the importance of power-dependant modulation of pressure and airflow in the system as it affects directly stack efficiency and dynamic response. In [13], numerical hybrid model was developed to describe the characteristics of turbo-compressors used in fuel cell applications. [14] focused on modelling static and dynamic operation of all components of fuel cell system to develop an off-design model of centrifugal compressors and understand the dynamic behaviour of fuel cell system. Whereas [15] used steady-state analytical model to optimise the design of fuel cell system quoting 3% increase in system efficiency by introducing serial booster and expander to screw compressor.

The idea of injecting water during air compression stage was proposed in [16, 17]. The injected water in [16] was used as lubricant and coolant for scroll type compressor. The rate of injection was found to be proportional to the isothermal efficiency of the compressor and directly affecting the air discharge temperature. In [17], a thermodynamic model was developed to investigate the water injection process in twin screw compressors. The effects of internal leakage and air-water heat transfer were validated against experimental data.

In this study, water injection in twin screw compressors will be examined. The injection is driven by the pressure difference between the injection point and compressor outlet pressure. This set-up which eliminates the need for water injection subsystem, such as water pump and other components, has the advantage of reducing the complexity of BOP and its energy requirements. The injected water is distributed at key locations in the system to enhance the efficiency of the compressor as well as to improve the humidity level of the air before entering the fuel cell stack. Humidity and temperature measurements were carried under various air flow rates (e.g. air supply) to cover wide range of fuel cell applications. The experimental results were used to estimate the power of fuel cell and compressor as a combined system to evaluate the overall BOP performance. These results provide better understanding of the humidification and cooling mechanisms and an insight into the design aspects for successful fuel cell-compressor integration.

2. Experimental Set-up

Figure 2 shows schematics of the experimental set-up which consists of the compressor, electric motor, water reservoir, water injector, and water separator. The compressor is a twin screw type with rotor diameter and length of 149.6mm and 231.9mm, respectively. The compressor operates between 3 and 15 bar of outlet pressure providing airflow of 2.4-3m^3/hour . The rotor profile, which is the ‘N’ type, is designed by City University London. This is based on a rack configuration but with modifications to the basic shape so that the best features of the basic rack are retained while most of the disadvantages are eliminated. The design thereby confers a number of advantages including greater flow area, stronger gate rotor lobes, reduced leakage and lower internal friction than those of alternative types of profile. More details about the design can be found in [18]. The compressor is driven by three phase AC motor. The motor operates with variable speed in the range of 296 – 2960 rev/min at maximum rated power of 75kW.

The water used for the injection is stored in 0.05m^3 reservoir. The stored water is pressurised by the system operating pressure and forced to travel to the injector nozzle. The nozzle is positioned in the middle section of the compressor chamber with an opening diameter of 5mm facing the female rotor. As the water enters the compression chamber, majority travels to the rotors forming sealant film between the blades. The remaining of the water passes to the suction and discharge bearings for lubrication. Two-stage water separator from Precision Pneumatics Ltd (Air receiver Atlas Copco) is installed at the end of the air flow line, after the discharge section of the compressor, to prevent the liquid water carried by the air stream from accessing the fuel cell stack.

Measurements of the air temperature and pressure are carried out at different locations in the system. The ambient (1) and suction (2) pressures were measured using pressure transducers Druck PDCR model 110/W over an operating range of 0-3.5 bar. For the discharge pressure (4) and the fluid pressure immediately before of the orifice plate (5) a PDCR model 922 was used with the operating range of 0-15 bar. The transducers have uncertainty of ±0.1% of the full range of the output (FRO). The sensor has maximum sampling rate and working pressure of 12kHz and 34bar, respectively. It operates at temperature range of -18°C to 93°C with an uncertainty of ±0.5% FRO. A differential pressure transducer, type PDCR 2120, was used to measure the pressure drop through the orifice plate (5). It operates at maximum pressure of 0.35bar with an uncertainty of ±0.1% FRO.

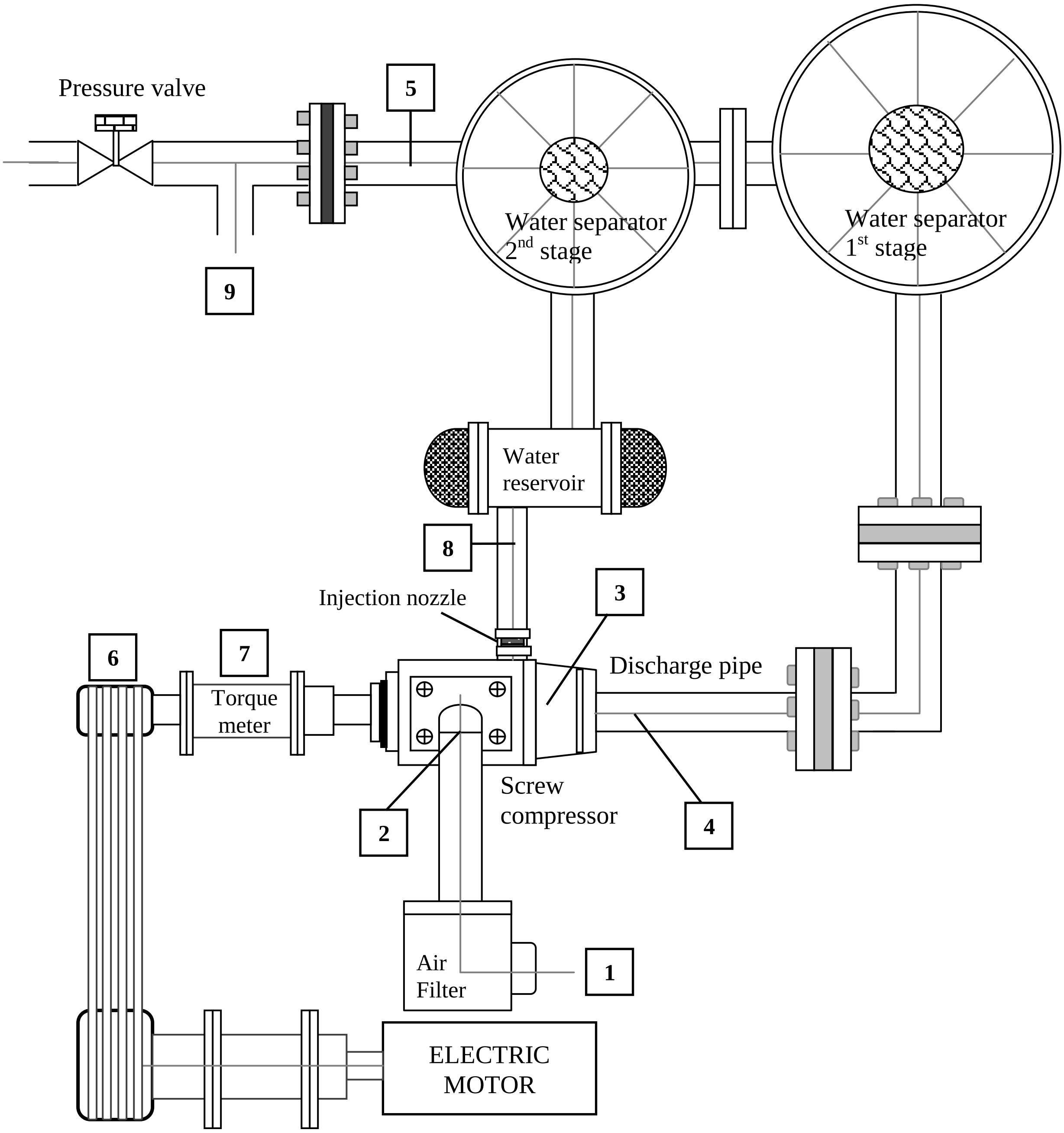

Figure 2 schematics of the experimental test rig

K type NiCr-NiAl - B thermocouples are used to measure the air temperatures at ambient (1), suction (2), discharge (4), and in front of the orifice plate (5). It is also used to measure the water temperature at the outlet of the water reservoir (8) before entering the compression chamber. The measurement range of the thermocouples is 0-300 [ºC] with an uncertainty of ±1% FRO. An optical frequency speed meter is used to measure the compressor rotational speed (6) where it is transferred to a data logger for analysis. An IML-TRP 500 torque meter transducer was used to measure the compressor driving torque (7). This covered a range of 0-500 [Nm] with an uncertainty of ±0.1% FRO and maximum shaft speed is 6000 rpm. The relative humidity and the temperature of the outlet air at the exhaust are measured using Thermo Hygrometer from TRACE (Part no.323i, ±5%). An opening from the discharge air stream (9) is made to the atmosphere to allow these measurements at ambient condition. All measurements were saved in workstation for further analysis.

3. Results and Discussion

The experiment was carried out in two consecutive stages. In the first stage, the system was adjusted to operate at steady state condition with a fixed temperature and discharge pressure of 100°C and 5 bar respectively. The second stage was to vary the rotor speed from 1500-3000rpm and saved the measured data in workstation1.

The experiment was carried out in two consecutive stages. In the first stage, the system was adjusted to operate at steady state condition with a discharge pressure of 5 bar. The next stage was to vary the rotor speed from 1500-3000rpm and the measure the temperature and relative humidity of the inlet and outlet air of the compressor

3.1 Effect on air flow condition

Figure 3 shows the change of air temperature at the suction/ inlet (T_{in}) and exhaust/ outlet (T_{out}) of the compressor under various operating speeds and mass air flow rates. Both temperature values increase with increasing the speed and similarly with the mass air flow. The increase of the inlet air temperature was affected by the additional heat generated during the mechanical work of the compressor. The more work exerted by the compressor for higher speeds, the more heat will be dissipated to the atmosphere which increases the temperature of the surrounding air at suction. The increase in temperature tends to be larger (~9C°) at low/medium speed range (1500-2500rpm) and gradually reduces (~2C°) at higher speed values (2500-3000rpm). This trend is the result of the warming-up of the compressor system before reaching steady-state condition. The increase of the inlet air temperature (11C°) was much smaller than the change of the outlet air (25C°). The temperature of the outlet air was increased due to the reduction in the water/air ratio, e.g. increase in air flow at higher speeds while the amount of water injection remains the same, which minimises the cooling effect of the injected water. The change in the outlet temperature was 25C° as the speed increased from 1500-3000rpm.

Figure 4 shows the effect of compressor speed and air mass flow rate on the relative humidity of the inlet and outlet air, RH_{in} and $RH_{out(inj)}$ respectively. It can be seen from the figure that both humidity values reduce with increasing the speed and air mass flow. This decrease was attributed to the increase in the inlet and outlet air temperature, as previously found in Figure 3. As the temperature increases, the saturation pressure of the water (P_{sat}) increases. The relative humidity, which is the ratio of water partial pressure (P_w) over the saturation pressure (P_{sat}), will consequently be reduced for higher temperatures. The reduction appears to be larger at lower speeds and relatively smaller at higher speeds. This trend is dominated by the exponential relationship between temperature and water saturation pressure. It can be also seen from Figure 4 that the relative humidity of the outlet air is higher than the inlet air for speed and air mass flow values below 2300rpm and 68g/s respectively. Although the temperature of the outlet air was found higher than the inlet, which one may expect its relative humidity will have lower value, the effect of water injection was evident in raising the relative humidity of the outlet air. Above these values (2300rpm/ 64g/s), $RH_{out(inj)}$ becomes lower than RH_{in}. The amount of injected water was not enough to compensate for the continuous increase of temperature. Therefore, for high operating speeds, more water injection is needed to prevent dry air supply to fuel cell stacks.

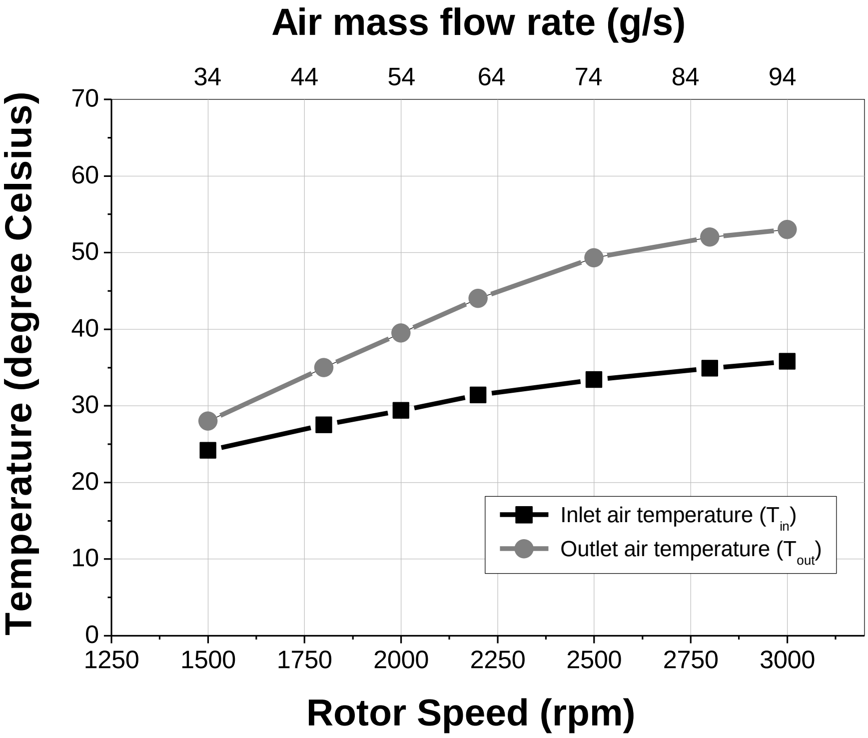

Figure 3 Effect of compressor speed/ air flow rate onto the temperature of the inlet and outlet air

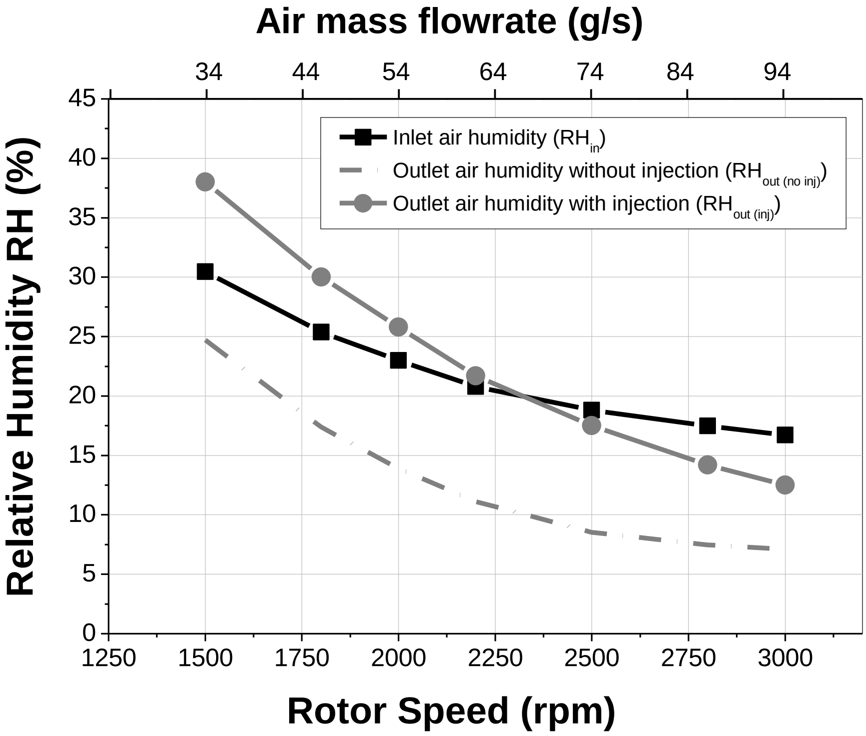

Figure 4 Effect of compressor speed/ air flow rate onto the relative humidity of the inlet and outlet air

The contribution of water injection to the change of the outlet air humidity can be quantified. Using the measured temperature values of the outlet air (T_{out}), the saturation pressure of water (P_{sat}) will be known. And since the measurements were carried under the ambient partial pressure (P_w), the relative humidity can be calculated. Figure 4 shows dotted line of the calculated RH for the outlet air $RH_{out(no\ inj)}$ in case of no water injection is taking place. This figure demonstrates clearly the impact of water injection in raising the outlet air humidity under different speed/ air mass flow conditions.

The rate of water evaporation and the change in relative humidity of the outlet air (ΔRH_{out}), e.g. with and without injection, are shown in Figure 5. The evaporation rate was increased by almost three times, from 20 to 62g/min, as the operating speed increased from 1500rpm to 3000rpm. The rate was slightly affected by increasing the temperature and largely by the increase of air mass flow rate. Meanwhile, the decrease in ΔRH_{out} was mainly dominated by the increase in temperature.

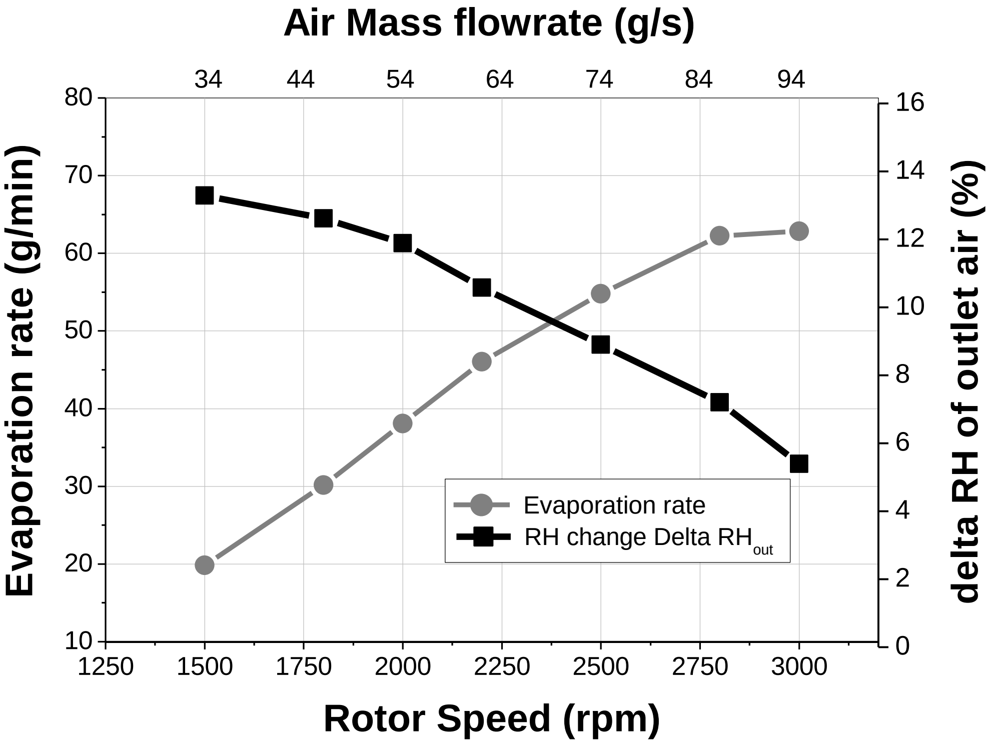

Figure 5 Change in relative humidity and evaporation rate at various compressor speeds/ mass air flow rats

3.2 Effect on fuel cell system power

Figure 6 shows the amount of power that was consumed by the compressor (P_{comp}) for different operating speeds and air mass flow rate. As shown from Figure6, P_{comp} increases steadily with an average of 1kw for 4g/s of air mass flow rate to reach a maximum value of 25kW at speed and air mass flow of 3000rpm and 94g/s, respectively. The figure also shows the amount of power that would be produced by the fuel cell for a given mass of supplied air. This power value (P_{FC}) was calculated from Equation1. The Balance-Of-Plant power (P_{BOP}) represents the excess in fuel cell power which can be used to run other components in the system, e.g. other than the compressor. The value of P_{BOP} was calculated by subtracting the power consumed by the compressor (P_{comp}) from the fuel cell produced power (P_{FC}).

It appears from Figure 6 that the more air mass flow provided to the fuel cell stack, the more surplus power of BOP. At air mass flow rate of 94 g/s, P_{BOP} reaches a value of 58kW. However, this large amount of air supply needs conditioning before entering the fuel cell stack. The temperature and humidity of the inlet air must be kept at the right level to prevent the fuel cell's membrane from flooding or drying which results in considerable degradation in the cell performance. It was found from previous measurements of Figure 4 that the relative humidity of the compressor's outlet air (or similarly the fuel cell inlet air) is inversely proportional to the air mass flow rate. This decrease will surely affect the estimated fuel cell power (P_{FC}). However, it is difficult to predict such drop in performance as it varies with the chemical, mechanical, and electrical design of the cell.

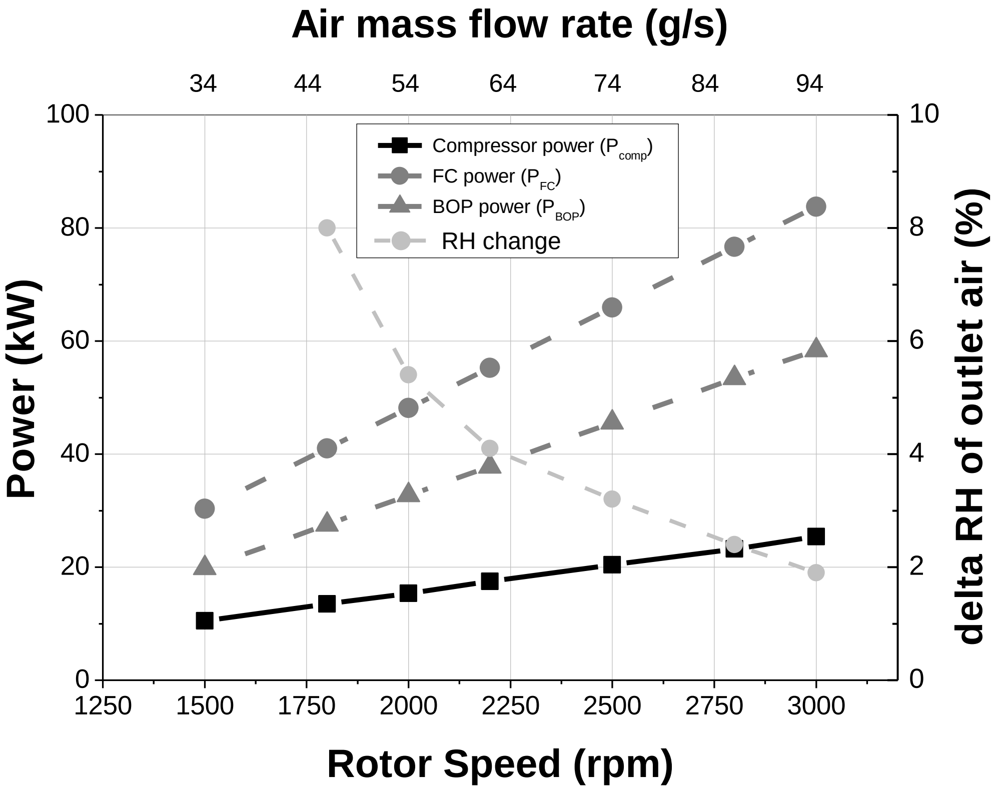

Figure 6 Compressor and fuel cell estimated power at different operating speeds and mass air flow rates

Conclusion

The injection of liquid water in Twin Screw compressors was investigated. The temperature and relative humidity of the air at suction and exhaust of the compressor were monitored under fixed pressure and water injection rate and at variable operating speeds.

The measurements show that both inlet and outlet temperatures are proportional to the operating speed and air mass flow rate. The increase in the inlet temperature was the result of increasing the compressor's mechanical work that generates additional heat to the surrounding atmosphere at suction. Meanwhile, the increase in the outlet temperature was due to the drop in water/air ratio which minimises the cooling of the injected water at higher speeds.

The temperature was found to be the main contributor to the change in relative humidity of the air. The humidity of the inlet and outlet air were reduced exponentially with increasing the speed and air mass flow rate, such trend determined by the relationship of temperature and water partial pressure.

The impact of water injection in raising the relative humidity of the outlet air was evident. The injection tends to affect humidity more at low operating speeds (~13%RH increase) and its effect becomes gradually less at higher speeds (~5%RH increase). Although at high speeds air humidity was minimum, mainly because of the reduction in water/air ratio under fixed injection, more humidification can be achieved as higher evaporation rate becomes available.

The rate of power produced by the fuel cell stack was higher than the rate used to run the compressor for the same amount of air supplied. The efficiency of the Balance-Of-Plant BOP was therefore higher when more air is delivered to the stack. However, this increase in the air supply needs additional subsystems for further humidification/ cooling of the BOP system.

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