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Continuous bubble humidification and control of relative humidity of H_2 for a PEMFC system

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ABSTRACT

The proton conductivity of perfluorinated ionomer membrane used in a proton exchange membrane fuel cell (PEMFC) depends largely on the extent of hydration state of the membrane. Sufficient membrane hydration is achieved typically through the humidification of gases prior to feeding them into the fuel cell. Further, hydrogen humidification is known to have a larger impact on the performance of a PEMFC than the oxygen humidification. Bubble humidification has been a widely used method to externally humidify hydrogen. However, to-date a continuous bubble humidification system, which is essential to the continuous operation of the PEMFC system, has not been implemented. The main contributions of this work are (i) a design for continuous humidification of hydrogen for the PEMFC system and (ii) a method to maintain the RH of hydrogen between 93 and 95% (at desired temperature) over a wide range of gas flow rates. One of the key advantages of the proposed design is the flexibility of using recirculated stack coolant water to increase the energy efficiency of the PEMFC system. The design is first tested off-line and then online with a 1 kW stack. Results obtained from both the off-line and online tests indicate that the design successfully meets the demands of an online operation. It is observed that with the use of the proposed humidification scheme, the stack efficiency in terms of power output increases by about 6–19% of the power obtained under dry hydrogen conditions.

1. Introduction

Fuel cells are electrochemical reactors, which directly convert chemical energy to electrical energy. Fuel cells are typically classified based on the type of electrolyte used in the cell. A widely studied fuel cell is the proton exchange membrane fuel cell (PEMFC), which attains its name due to the use of polymer membrane as electrolyte. PEM fuel cells are considered to be a potential energy device in automobile and residential applications because of their advantages over other fuel cells in terms of quick start-up, high power density and low operating temperature [1].

The most commonly used membrane is the perfluorosulfonic membrane (usually Nafion®). The efficient performance of a PEM fuel cell based on such a membrane is heavily dependent on the water management within the cell. This is linked to the fact that in such cells, protons are transferred from anode to cathode as hydronium ions (H_3O^+) and the proton conductivity depends on the hydration of the membrane [2]. Water transport across the membrane occurs in three ways: (i) electro-osmotic drag, (ii) diffusion, and (iii) convection. For good proton conductivity, the membrane water content (λ) should be maintained at values close to 14 water molecules/membrane charge site throughout its thickness (for

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a membrane thickness of 50 μm). At low current densities, i.e. below 0.1 A/cm^2, the water transport by back diffusion is sufficient to meet the aforementioned requirement. On the other hand, at high current densities, i.e. above 0.1 A/cm^2, the water transport from cathode to anode side by back diffusion is not sufficient to meet the requirements of membrane hydration. This eventually leads to a drop in the flux ratio H_2O/H^+ due to electro-osmotic drag [3–5]. Therefore, to keep the membrane hydrated, the reactant gases need to be humidified before they are fed into the cell. In general, the performance of the fuel cell is dependent more on hydrogen humidification than on the oxygen humidification [6,7]. Furthermore, the *net power* output is lower when both the reactants are saturated than when the hydrogen alone is saturated and fed into the cell [8]. With these facts in mind, humidification of hydrogen for PEM fuel cells on a continuous basis is developed in this work.

There are a variety of approaches available to humidify the reactant gases. These humidification approaches can be broadly classified into internal and external humidification schemes. In internal humidification, the gases are heated externally but humidified within the cell, while in external humidification, the gases are heated and humidified external to the cell. External humidification is preferred to internal humidification at high temperatures [6].

The humidification scheme proposed in this work is based on external humidification. In external humidification, the gases can be humidified in two different ways, through (i) direct steam injection and (ii) bubble humidification. The choice of one method over the other is governed by two factors: (i) the power consumed by the scheme and (ii) the power gain (increase in the stack power) by implementing that method. In case of automotive applications where stacks of high capacities are used, the power consumed in humidifying the gases by steam injection method is relatively low when compared with the power of stack gained by using this method. Therefore, the steam injection method is widely used in automobile applications. On the other hand, in residential applications, which primarily involve the use of low power stacks (below 5 kW), the power used for steam injection is prohibitively high when compared with the increase in stack power. In contrast, for low power stacks, the bubble humidification scheme results in an increase in stack power that is significant when compared to the amount of power used for humidification. The proposed scheme further reduces the power consumption requirements of this scheme. The bubble humidification scheme, therefore, is a preferred choice over the steam injection method for residential applications.

In bubble humidification, the gas is finely bubbled through the water column termed as the humidifier. This scheme also facilitates good control over the RH of the gas. A possible disadvantage of this scheme is that it can add to the bulk of the system. Despite this fact, the simplicity and the ability to control the RH make the bubble humidification method a preferred choice over the steam injection method where the stack capacities are below 5 kW.

The parameters that influence the RH of the reactant gas in a bubble humidifier are known to be gas residence time in the humidifier, temperature of humidifier bottle and diameter of sparser hole [9]. However, a few important issues are associated with bubble humidification exist and have not been addressed to-date. Firstly, the gas–vapour mixture can cool and condense on the path way leading to the stack inlet as water droplets. These droplets then directly enter the stack and deteriorate the stack performance. In order to avoid this situation, experiments have to be conducted at room temperature or alternatively the gas pipe has to be heated to prevent condensation [10]. Secondly, a carry-over of liquid water occurs at high gas flow rates [9]. In addition to these issues, an important fact is that there is no existing method for continuous humidification and control of RH of H_2 at desired temperature using bubble humidification.

In this work, a design methodology is proposed for continuous humidification and control of RH using coolant water recirculation. The underlying motive is to meet the humidity requirements of the H_2 gas at near stack temperatures combined with an efficient utilization of the stack thermal energy. With such a scheme, the RH of H_2 gas can reach values between 93 and 96% at temperatures close to *stack temperature*. Alternatively, if the objective is to achieve the required RH at a *specific temperature* of H_2 gas, the proposed scheme allows the use of external hot water recirculation. However, there are several advantages in using recirculated coolant water as heating and humidification media, which are listed below as follows.

- No additional thermal energy is required in the form of electricity for heating the humidifier bottle resulting in a decrease in parasitic power losses.
- The amount of electricity consumed by the radiators to cool the stack coolant water temperature can be reduced by a significant amount.
- Condensation of water vapour that causes flooding at the electrode-flow field interface can be avoided irrespective of the stack operating temperature.

An immediate benefit of the above advantages is that no additional operating costs are required for H_2 humidification in the form of electricity when compared with the conventional bubble humidifier and external hot water recirculation schemes. Further, the operating costs involved for cooling the stack coolant water can be reduced by a significant amount, i.e. power consumed by the radiators. One can justify considering the above facts that the proposed design leads to an increase in *efficiency of the fuel cell system* in terms of net power. For the experimental studies presented in this work, external hot water recirculation is used for off-line testing of proposed design, while the recirculated stack coolant water is used for online implementation with 1 kW stack. To the best of authors' knowledge, there is no such design available in the literature, which can humidify and control the RH of H_2 on continuous basis using a bubble humidifier.

This paper is organized as follows. Section 2 describes the conventional bubble humidification scheme used to study the factors influencing RH of H_2. The proposed modifications for continuous humidification of H_2 gas are described in Section 3. The mechanism of proposed design to control RH of H_2 is presented in Section 4. Experimental results obtained by implementation of the proposed design on 1 kW stack are

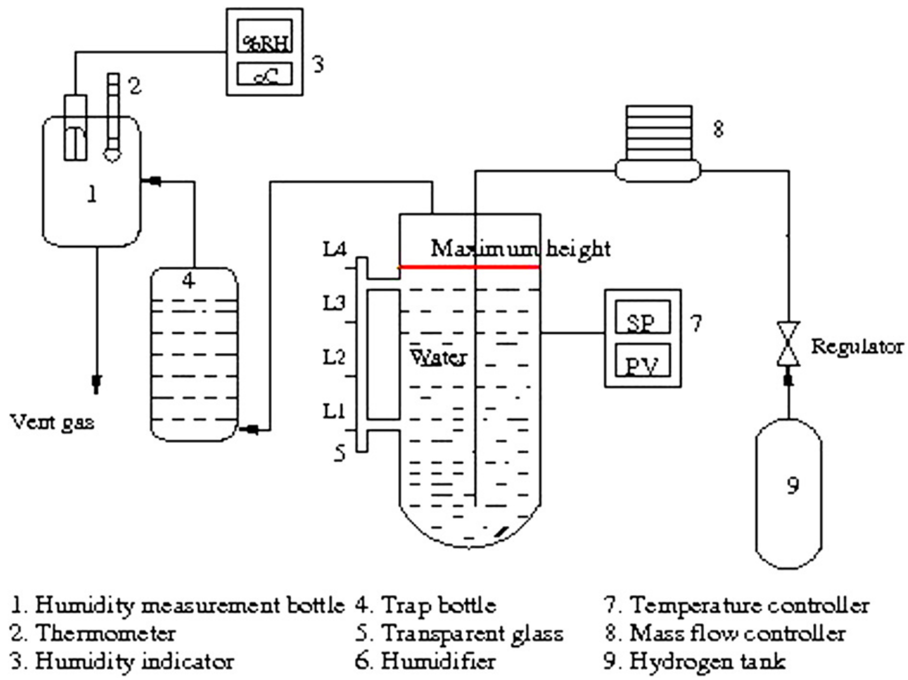

Fig. 1 – Schematic of a bubble humidification system.

presented in Section 5. The paper ends with concluding remarks and directions for future work in Section 6.

2. Experimental studies of factors influencing RH

To design a continuous humidifier to control the RH of H_2 gas at desired value, the effect of parameters (water level and humidifier temperature) which influences the RH of H_2 is studied experimentally using a conventional bubble humidifier setup.

2.1. *Experimental setup*

The bubble humidification setup for this purpose is composed of a humidifier vessel of size 1850 cm^3, whose schematic is shown in Fig. 1. The gas is allowed to pass through the feed sparser pipe of humidifier bottle, which contains 25 holes of 1 mm diameter at the bottom. The exit gas from the humidifier goes through the trap bottle where the liquid droplets are removed and then passed into humidity measurement bottle. The RH and temperature of gas are measured at steady state in the humidity measurement bottle using a humidity indicator and a thermometer, respectively. Finally the gas exits at the bottom of humidity measurement bottle.

The temperature of humidifier bottle is controlled by a jacketed electrical heater, while the gas flow rate is controlled by using a mass flow controller. The humidifier bottle, trap bottle and humidity measurement bottle are connected closely to minimize the heat losses between the humidifier and the humidity measurement bottle. The experiments are conducted for different water levels (L1: 320 cc; L2: 580 cc; L3: 800 cc; and L4: 1000 cc) at constant humidifier temperature (40 °C) and for different humidifier temperatures (40, 50, and 60 °C) at constant water column height (L1) in the humidifier. The water level in the humidifier is maintained almost at constant value during experimental runs by periodical addition of water into the bottle. The data were collected for temperature and RH when the water level and temperature of H_2 in humidity measurement bottle had reached the steady state.

2.2. *Observations*

2.2.1. *Effect of water level*

It is inferred from Fig. 2 that at low gas flow rates (0.5–4 lpm), a significant increase in RH of H_2 is observed at different levels

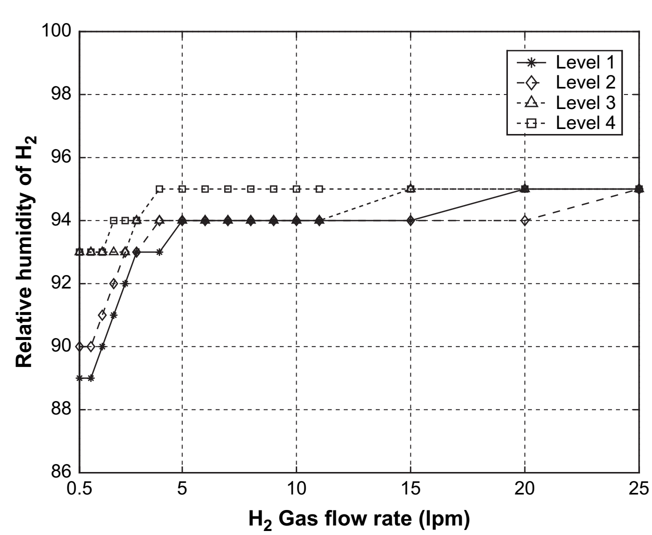

Fig. 2 – RH of H_2 at $T_{humidifier} = 40$ °C.

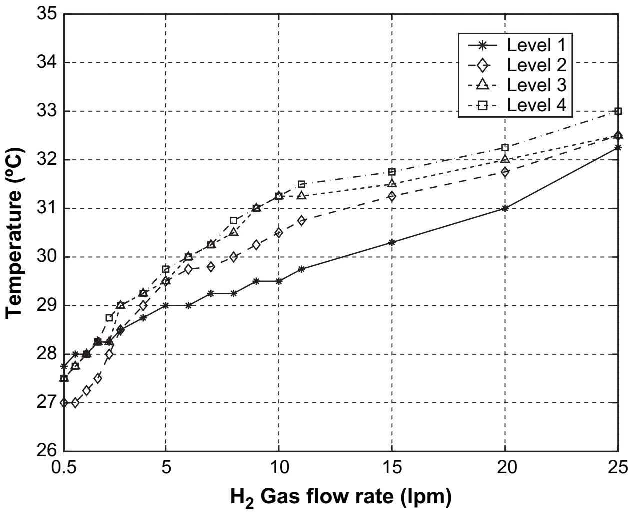

Fig. 3 – Temperature of H_2 gas.

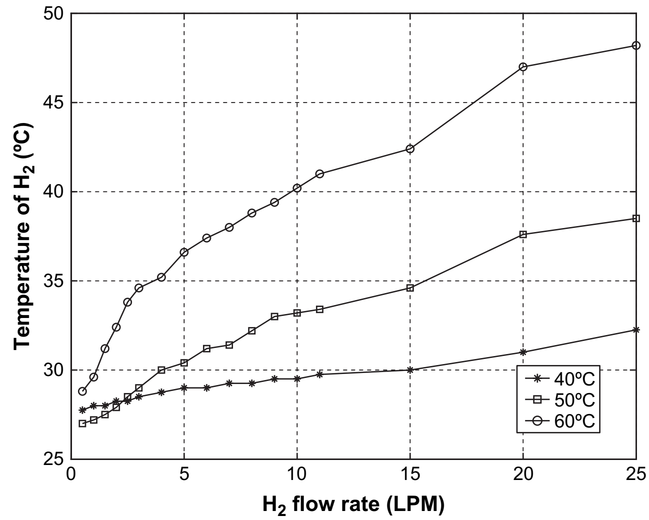

Fig. 5 – Temperature of H_2 gas for different humidifier temperatures at level 1.

of water volumes in the humidifier bottle. At low gas flow rates, the RH of H_2 is predominantly influenced by gas residence time in the humidifier. On the other hand, at high flow rates of gas, the effect of gas residence time on RH of H_2 is negligible and independent of water level in the humidifier. From Fig. 2, it is observed that the RH of H_2 is 94 and 95% at level 1 (L1) and level 4 (L4) respectively, when gas flow rate exceeds 4 lpm. Fig. 3 shows that at any gas flow rate, the temperature difference of exit gas between any two levels is less than 1.5 °C. Since the exit gas temperature does not vary much, the RH of H_2 stays almost at constant value for high gas flow rates.

2.2.2. *Effect of humidifier temperature*

It is inferred from Fig. 4 that at low gas flow rates (0.5–4 lpm) there is a significant increase in RH from 93 to 95% observed with an increase in humidifier temperature from 40 to 60 °C. The RH stays constant at 95% after 4 lpm of gas flow rate

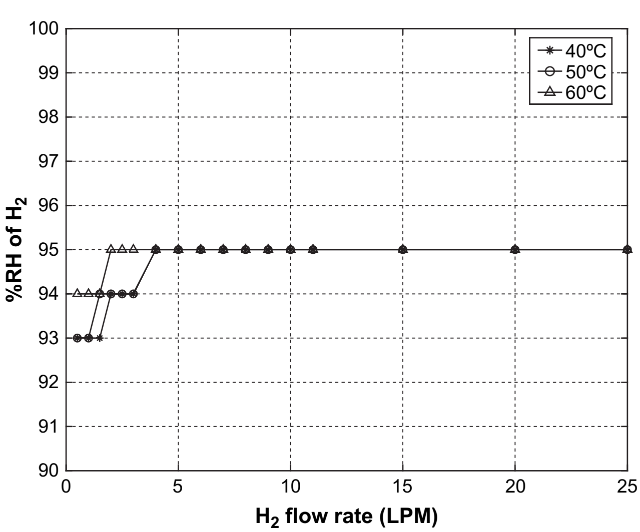

Fig. 4 – Relative humidity of H_2 for different temperatures of humidifier bottle at level 1.

this implies that the RH is independent of humidifier temperature after 4 lpm of gas flow rate. It is inferred from Fig. 5 that the desired temperature of H_2 at exit can be achieved by maintaining the humidifier higher than the desired temperature of H_2 exit gas. The temperature of H_2 cannot be achieved a constant value over a wide range of gas flow rates due to loss of water vapour leading to the path way of hygrometer vessel from humidifier.

The above studies suggest that the RH of exit H_2 as minimum as 93% can be achieved if the water level is maintained at L4 for the regime of low gas flow rates (0.5–4 lpm). After 4 lpm of gas flow rate, the RH is independent of water level and temperature of humidifier. It is observed that the liquid water carry-over occurs at level 4 when the gas flow rate exceeds 5 lpm. No liquid carry-over by the gas is observed at level 1 when the gas flow rate does not exceed 25 lpm. To achieve these requirements, a new design is developed to meet the objective of dynamic water shift which can eliminate liquid water carry-over and ensures the RH of H_2 is controlled between 93 and 96% for a wide range of gas flow rates (1–20).

3. Proposed design for continuous humidification of H_2

Based on the experimental results obtained, the conventional bubble humidifier is modified to meet the requirements of continuous humidification. The modified setup is shown in Fig. 6. The additional components that have been introduced are (i) level control bottle (LCB), (ii) exit gas heating section, and (iii) water pump. The level control bottle facilitates dynamic adjustment of water level within the humidifier with the change in gas flow rate. This is made possible by a 'T' connector between the humidifier and the LCB, and a float ball valve mechanism (described in Section 4.1). The exit gas heating section is provided mainly to avoid the water vapour condensation between the stack and the humidifier exit. A pump

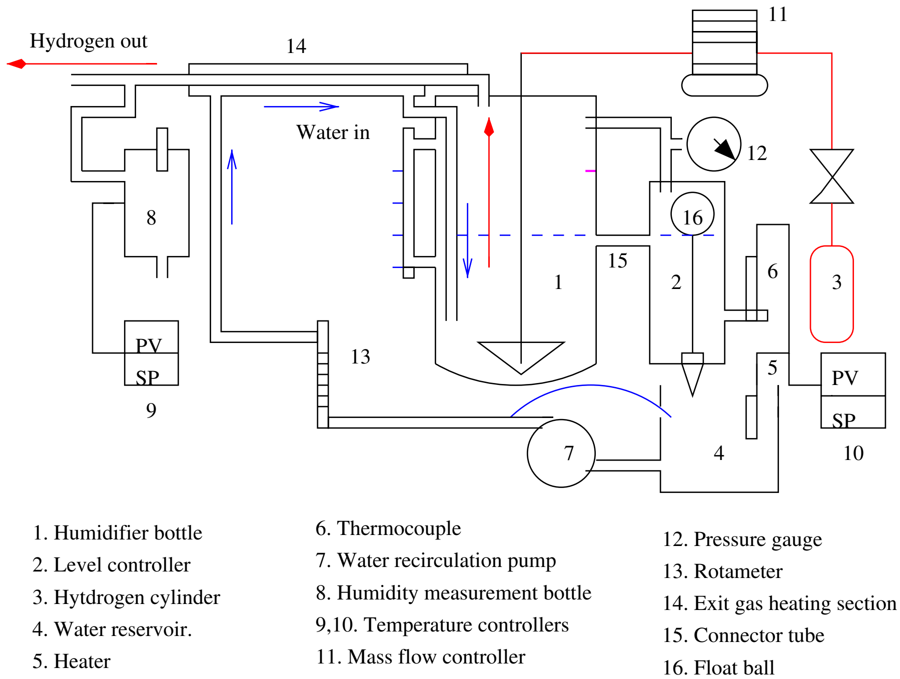

Fig. 6 – Schematic of a continuous humidification system.

is used to provide continuous supply of water into the humidifier by recirculation.

The humidifier is maintained at a temperature of 55 °C using a temperature controller, which heats the water that enters the humidifier as shown in Fig. 6. First and foremost, the water has to be pumped into the humidifier to avoid initial gas leakage. Water circulation flow rate initially (prior to enter the gas into humidifier, i.e. zero gas flow rate) set to a fixed value such that the water level in humidifier is at maximum height (L4). The excess water is then bypassed back to the reservoir. The water is passed into the humidifier after it is circulated around the humidifier exit gas pipe. The H_2 gas flow rate is controlled using a mass flow controller. A pressure gauge has been used to measure the gauge pressure in level control bottle. Data are collected when the water level in the humidifier reaches steady state at each gas flow rate.

3.1. *Features of continuous humidification design*

- Provision to fix the maximum water height in the humidifier corresponding to a minimum gas flow rate at which liquid water carry-over starts.
- Prevention of condensation of water vapour by heating of exit gas with recirculated hot water.
- Continuous humidification of H_2 gas without any interruption to the stack operation.

4. Control of relative humidity of H_2

The control scheme is designed such that the RH of H_2 is controlled between 93 and 96% for a wide range of gas flow rates (1–20 lpm) without any water droplets carried by the gas.

At low gas flow rates the gas is allowed to reside in the humidifier for a sufficient period of time. This is made possible by maintaining maximum water level (L4) for the regime low gas flow rate. To maintain the water level at maximum height (L1), the design is tuned such that there is no significant deviation in water level for the range of 1–5 lpm of gas flow rates when it is tested off-line or connected online with a stack. This can be done by adjusting a needle valve at the exit of humidifier or anode side of a stack. On the other hand, at high gas flow rates the water level has to decrease to minimum level (L1) to avoid liquid water carry-over. In this high flow rate regime, minimum water level is sufficient since the RH is more or less independent of water level as observed in Section 2.2. In essence, the water level has to be dynamically adjusted with change in gas flow rates, which is achieved by a float ball level control mechanism explained in Section 4.1.

4.1. *Mechanism of float ball level control system*

The mechanism involved in water level control bottle is a float ball connected to a metal stopper with the help of a cotton thread. Initially, the conical metal stopper closes the water drain hole. As the water enters the control bottle, the float ball rises and lifts the stopper thereby allowing the water to drain out. The water drain is closed automatically by the metal stopper when the water level reaches a minimum height (4.5 cm) in the level control bottle. A minimum water level of 4.5 cm in the level control bottle is required to avoid gas leakage from the level control bottle. The gas leakage occurs when the water level in the bottle falls below 3 cm. The maximum water level in the level control bottle should be lower than the height at which the connector tube (stem) is connected. This is to prevent a two-way interaction with the humidifier.

The mechanism described above works well provided the float ball is not submerged. Float ball is submerged when the gravity force and pressure force acting combinedly on the valve exceeds the buoyancy force of a float ball. In order to avoid flooding of water in the humidifier, the system should be operated always below the limiting operating pressure, which is described in detail in Section 5.1.

5. Results and discussion

Before the design is tested online, the limiting conditions of the proposed design are studied in off-line mode. These studies help mainly to identify the limits under which the gas flow rate, operating pressure and water level in the humidifier have to be maintained for the safe operation of design without fail during continuous run.

5.1. *Limiting operating pressure, gas flow rate and water flow rate*

Beyond a certain pressure of the humidifier the water drain from the level control bottle (LCB) remains closed resulting in the build up of water in LCB. Subsequently, this situation leads to flooding in the humidifier. The pressure at which this phenomenon occurs is termed as *limiting operating pressure*.

The limiting operating pressure in this study is found by placing two different float balls in the level control bottle. The float balls are made-up of high density polyethylene (diameter 6.1 cm) and thermo coal (diameter 6.1 cm and height 6.1 cm), which are hollow spherical and cylindrical in shape, respectively. The observations of the limiting operating pressure for the two float balls are tabulated in Table 1. It is inferred from Table 1 that the limiting pressure is higher for cylinder than the sphere of the same size. This is due to the fact that the cylinder has higher volume than the sphere, which leads to higher buoyancy force. In the present experimental setup, the limiting pressure is observed to be 120 mbar when the cylindrical ball is used. The humidifier is flooded and no water drain from the level control bottle is observed when the operating gas pressure in the humidifier exceeds the limiting pressure.

In general, water carry-over occurs at high gas flow rates. The maximum gas flow rate is fixed for a particular design setup. The water level in the humidifier decreases gradually to a minimum value (L1) with an increase in gas flow rate. The gas flow rate at which the water carry-over occurs at minimum water height (L1) in the humidifier is termed as *limiting gas flow rate*. In the present experimental setup, the limiting gas flow rate is observed to be 25 lpm. Water carry-over occurs

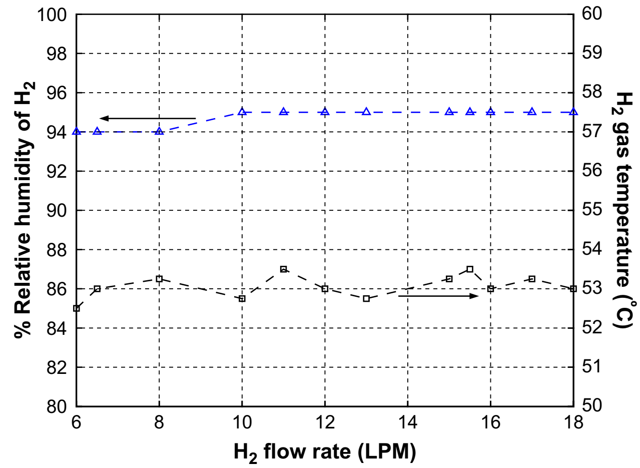

Fig. 7 – RH of H_2 at 53 °C and exit gas temperature; humidifier temperature at 55 °C.

even at low gas flow rates if the water level in the humidifier exceeds a maximum height, which is affected by the water flow rate into the humidifier bottle. The water flow rate for which the height of water level in the humidifier reaches the maximum (L4) is termed as *limiting water flow rate*. The limiting water flow rate is observed to be 1.8 lpm for the present setup.

5.1.1. *Off-line testing – control of RH*

Off-line testing is carried out by using the external hot water recirculation as the heating and humidification media of H_2 as shown in Fig. 6. The RH of H_2 was measured at constant temperature (53 °C) in humidity measurement vessel, which was maintained by a temperature controller. The temperature of H_2 was measured after it passed through the recirculated heating section. The RH and temperature of H_2 are shown in Fig. 7. It is observed from Fig. 7 that the RH of H_2 is almost constant (94–95%) over a wide range of gas flow rates (6–18 lpm). The region of low gas flow rates (1–5 lpm) is not shown here because there is no water carry-over observed in this range of flow rates. From the above results, it is clear that the RH of H_2 is controlled at constant value (94–95%). Besides, the dynamic shift of water level in the humidifier from maximum (L4) to minimum (L1) value resulted in elimination of water carry-over at high gas flow rates. Since the exit gas is heated by a circulated hot water, the condensation of water vapour is avoided before it is measured in the measurement bottle.

To control the humidifier temperature at 55 °C, the hot bath temperature is increased gradually from 57 to 60 °C as the gas flow rate changed from 1 to 18 lpm. The temperature of the exit H_2 fluctuates around the value of 53 °C. It is due to the change in temperature of circulated water by which

Table 1 – Comparison of different float balls for limitation of operating pressure

Float ball type	Type of material	Diameter/length (cm)	Mass (g)	Limiting pressure (mbar)
Hollow sphere	HDPE	Diameter = 6.1	28.62	60
Cylinder	Thermocoal	Diameter = 6.1; height = 6.1	27.25	120

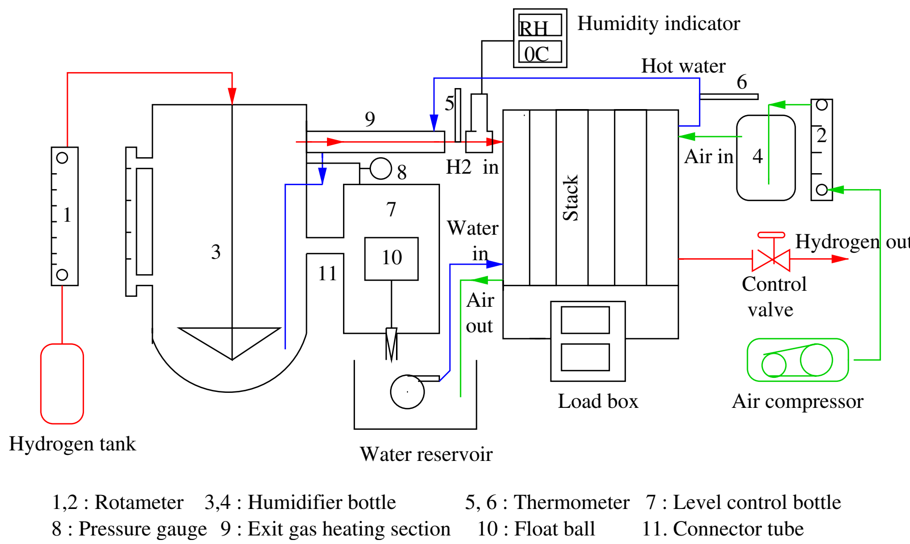

Fig. 8 – Schematic of continuous humidification of H_2 using recirculated stack coolant water.

the exit gas is heated. RH of H_2 is observed to be constant (94–95%) as shown in Fig. 7. These recordings were noted at exit gas temperature which remains approximately constant at 53 °C over a wide range of gas flow rates. It is inferred that the RH of H_2 is controlled at 94–95% at desired temperature (53 °C) of exit gas. This implies that the 95% of RH of H_2 at the humidifier exit can be achieved at stack temperature by maintaining the humidifier temperature higher than at the stack temperature. The temperature of exit gas is obtained nearly constant (53–53.75 °C) at low and high gas flow rates due to sufficient heat supplied by the recirculated hot water at gas heating section. The major advantages of hot water recirculation around the exit gas pipe is that the exit gas temperature is controlled almost at constant value and that the condensation of water vapour carried by the gas can be avoided.

5.2. *Online testing with stack*

Experiments were conducted by connecting the humidifier to a 1 kW PEMFC stack developed at the Centre for Fuel Cell technology (CFCT), Chennai, India. The stack coolant water is used as the humidification and heating media for H_2 instead of the external hot water circulation that is used for off-line studies, the advantages of which were elucidated in Section 1.

The objectives of the online test were two-fold to (i) test the performance of the proposed continuous humidifier design in meeting the design objectives over a wide range of gas flow rates and (ii) evaluate the increase in stack efficiency in terms of power when compared with the stack operated with dry H_2.

The continuous humidifier setup was connected to the anode side as shown in Fig. 8 and the complete design data pertinent to this schematic is provided in Table 2. The thermometer and humidity indicator were kept across the gas flow for online measurement of temperature and RH of H_2. A submersible pump was used for water recirculation. The initial recirculated water flow into the humidifier was adjusted to 0.8 lpm where the H_2 flow is 18 lpm. On the cathode, a conventional bubble humidifier was used for *air humidification* and the temperature of humidifier was maintained at 50 °C using a temperature controller. Water droplets carried by the air were removed in a liquid trap bottle before the air was fed into the stack.

Initially, the flow rates of H_2 and air were kept at 18 lpm and 120 lpm, respectively. The voltage was fixed at 21 V and sufficient time was given to allow the stack temperature to reach the steady state value of 52 °C. At this point, current and the power output of the stack were 38 A and 800 W. Readings were then obtained at different voltages (27 V, 23 V, and 22 V) using an electronic load box. This procedure is repeated for different flow rates of H_2. No temperature control was

Table 2 – Design specifications of stack and continuous humidifier setup

Stack	
Capacity	1 kW
Active area	236 cm^2
Number of cells	38
Length of the stack	30 cm
Cross sectional area	17×21 cm^2
Humidifier bottle	
Humidifier diameter	11 cm
Height of the humidifier	20 cm
Diameter of gas sparser	0.1 cm
Gas distributor diameter	5 cm
Exit gas heating tube length	15 cm
Level control bottle	
Diameter	8 cm
Float ball material	Thermocoal
Float ball diameter	6.1 cm
Float ball height	6.1 cm
Bottle exit diameter	1 cm
Connector tube diameter	0.6 cm
Maximum operating pressure	120 mbar

Table 3 – Table of comparison of power delivered under dry and humidified conditions of H_2 of 1 kW stack

H_2 flow (lpm)	Voltage (V)	Humidified H_2			T_{st} (°C)	Dry H_2		Efficiency $= ((P_{humid} - P_{dry})/P_{dry}) \times 100$
		%RH	Current (A)	Power (W)		Current (A)	Power (W)	
18	27	95	20.5	553.5	51	18.31	494.37	11.96
	23	95	36.7	844.1	51	33.22	764.06	10.47
	22	95	37.2	818.4	51	34.2	752.4	8.77
	21	95	38	798	51	35	735	8.57
15	27	95	20.2	545.4	48	17.6	475.2	14.77
	23	95	33.5	770.5	48	31.6	726.8	6.12
	22	95	34.7	763.4	48	32.8	721.6	5.73
	21	95	36.6	768.6	48	34.4	721.5	6.52
12	27	95	18.3	494.1	42	16	432	14.37
	23	95	30.2	694.6	42	28	644	7.85
	22	95	32	704	42	30.5	671	7.89
	21	95	35	735	42	32	672	9.37
10	27	95	18.12	489.24	38	15.59	420.93	16.22
	23	95	28.15	647.45	38	26	598	8.29
	22	95	30.11	662.42	38	27.5	605	9.31
	21	95	30.9	648.9	38	28.7	602.7	7.66
8	27	95	11.52	311.04	37	10.42	281.34	10.55
	23	95	17.81	409.63	37	15.67	360.41	13.65
	22	95	22.12	486.43	37	19.8	435.6	11.74
	21	95	25.08	526.68	37	21.57	452.97	16.27
5	27	94	6.91	186.57	36	5.84	157.68	18.32
	23	94	9.48	218.04	36	8.12	186.76	16.75
	22	94	13.12	288.64	36	11.56	254.32	13.5
	21	94	14.12	296.52	36	12.68	266.28	11.35
3	27	93	1.82	49.14	32	1.56	42.12	16.6
	23	93	3.33	76.59	32	3.04	69.92	9.5
	22	93	3.47	76.34	32	3.23	71.06	7.4
	21	93	3.97	83.37	32	3.37	70.77	17.8

provided to control the stack temperature. The complete set of readings are tabulated in Table 3.

5.2.1. *Performance evaluation*

The variations in the RH of H_2 with increase in H_2 flow rate for the experimental conditions described above are tabulated in Table 3. It is inferred from Table 3 that there is no water carry-over for a wide range of gas flow rates; otherwise, the RH would have reached 100. Thus, this test successfully demonstrated the capability and potential of controlling the RH of H_2 at constant value (93–95%) without liquid water carry-over over a wide range of H_2 flow rates.

It may be observed that a decrease in stack temperature with the decrease in gas flow rate takes place, which is explained as follows. A gradual decrease of pressure in the humidifier with the decrease in H_2 flow rate results in a decrease of back pressure on the water pump. This causes an increase in the water flow rate, which in turn decreases the stack temperature.

A decrease in temperature of coolant water by 0.5–1.25 °C is observed experimentally when the H_2 flow rate was changed from 5 to 20 lpm. The temperature of stack coolant water (recirculated) can be brought down further by humidifying the air in the same way, demonstration of which is beyond the scope of this paper. Therefore, the increase in overall *efficiency of the fuel cell system* in terms of net power (stack power minus power consumed by auxiliaries) can be achieved. This is due to decrease in power that is used to cool the stack exit coolant water. As mentioned in Section 1, condensation of water vapour that causes flooding at the electrode-flow field interface can be avoided regardless of the stack operating temperature. This is due to the fact that the gas mixture enters the stack at a temperature below, but close to stack temperature. This can be observed from Fig. 7 which shows that the exit H_2 temperature is below the humidifier temperature (55 °C).

5.2.2. *Evaluation of stack efficiency*

In order to assess the improvement in the stack efficiency with the proposed method vis-a-vis the stack operation under dry conditions, the hydrogen gas was fed to the stack by-passing the humidifier module. The rest of the experimental conditions including air humidification were maintained identical to that used in the humidified case. Readings for the delivered current and stack power are tabulated in Table 3. The increase in stack efficiency (η) is calculated as

$$\eta = \frac{\text{Power}_{\text{humid}} - \text{Power}_{\text{dry}}}{\text{Power}_{\text{dry}}} \times 100 \quad (1)$$

The calculated values at various flow rates of H_2 are tabulated in the last column of Table 3.

The increase in stack efficiency is observed to be in the range of 6–19% (of the power under dry conditions) over a wide range of H_2 flow rates. Thus, one obtains a significant enhancement in the stack efficiency with respect to the power delivered. Further, it can be inferred from Table 3 that the stack shows high efficiency at high voltages. This is due to the fact that the membrane offers low resistance at lower currents. Also, the membrane may be maintained under well-hydrated conditions that can enhance the proton conductivity under such conditions.

6. Conclusions

In this work, the conventional bubble humidifier has been modified to a continuous humidifier to control the RH of H_2 at constant value (94–95%) (near stack temperatures) using stack coolant water recirculation. Alternatively, an external hot water recirculation can also be employed, which then gives the feature of achieving desired RH at a given temperature. The proposed design overcomes the drawbacks of a conventional bubble humidifier, namely, liquid carry-over and vapour condensation. The main advantages of the proposed design are (i) control of RH at desired value, (ii) recycling of thermal energy, (iii) no liquid carry-over at high gas flow rates, and (iv) no water vapour condensation at the stack inlet and humidifier exit channel. The modified design has been tested with a 1 kW PEM fuel cell stack using recirculated stack cooling water as the heating and humidifying medium. The performance test has shown that the proposed design successfully achieved its objectives and achieved 6–19% enhancement in stack efficiency (in terms of the power under dry conditions).

The new design meets the RH requirements by ensuring maximum residence time at low flow rates and minimum residence time at high flow rates, which also avoids liquid water carry-over. This is achieved by a dynamic water level adjustment in the humidifier with changes in gas flow rate. The float ball size and connector tube diameter are the crucial design parameters in the design of a continuous humidifier. The proposed design is functional up to 25 lpm gas flow rate, but is scalable to higher gas flow rates. Future work involves an in-depth study of heat integration by extending it to air humidification and scaling of proposed design to high capacity stacks.

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