DESIGN OF A 500 W PEM FUEL CELL TEST SYSTEM

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Abstract

This paper describes the design of a 500 W PEM fuel cell test system which can be used for both validating fuel cell models and for measuring the fuel cell model parameters. The software controllable operation and wide operating range of the fuel cell test system is such that a variety of control strategies may be implemented and tested. In this paper the major difficulties in the design of the PEM fuel cell test system are presented and options for further development work are discussed.

1. INTRODUCTION

The Polymer Electrolyte Membrane (PEM) fuel cell is particularly well suited for electrical vehicle and other mobile applications because of its high power density, low operating temperature, and fast response times. However, in order to make best use of PEM fuel cells in practical applications, an accurate model is required to simulate the fuel cell performance. For the case where these models are still being developed and require validation, or where parameter measurements are required for the application of the model, then a PEM fuel cell test system is required.

Described in this paper is the design of a 500 W PEM fuel cell test system to be used for both model parameter determination and model validation. The PEM fuel cell test system features software controllable operation and data acquisition of the critical operating parameters for the PEM fuel cell over a wide range of operating conditions

2. PEM FUEL CELLS

A fuel cell is an "electrochemical cell which can continuously convert the chemical energy of a fuel and an oxidant to electrical energy by a process involving an essentially invariant electrode-electrolyte system" [1]. For the PEM fuel cell, hydrogen is used as the fuel and oxygen is used as the oxidant. The hydrogen and oxygen react electrochemically at the anode and the cathode electrodes respectively, and the net products are dc power, heat, and water. The electrochemical reactions are [2],

Anode reaction: $$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

Cathode reaction: $$\tfrac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (2)$$

Net reaction: $$\tfrac{1}{2}O_2 + H_2 \rightarrow H_2O \quad (3)$$

2.1 Physical Structure

The physical structure of the PEM fuel cell consists of a PEM in contact with an anode and cathode electrode on either side. The PEM prevents the direct mixing of the hydrogen and oxygen gases but allows the conduction of the hydrogen ions from the anode to the cathode electrode. The electrons are conducted from the anode to the cathode electrode by an external path to perform useful work [3]. A diagram of a PEM fuel cell with the reactant and product gases and ion conduction flow is shown in figure 1.

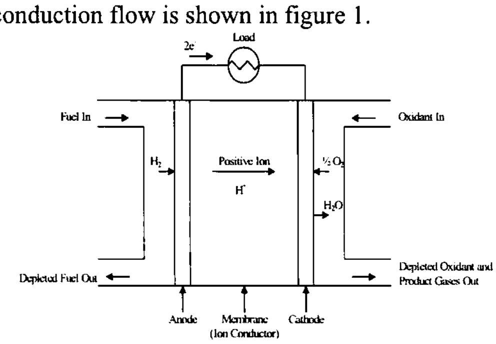

Figure 1 Operation of PEM Fuel Cell [3]

2.2 Performance

The characteristic performance of the PEM fuel cell at a given set of operating conditions is expressed in a polarisation curve which is a graph of the fuel cell voltage against current. The efficiency of the fuel cell is then determined from the percentage ratio of the operating cell voltage relative to the ideal cell voltage, and the power of the fuel cell can be determined from the voltage and current.

The actual operating voltage is less than the ideal voltage because of the irreversible losses associated with the fuel cell electrochemistry. The three primary irreversible losses that result in the degradation of fuel cell performance are activation polarisation, ohmic polarisation, and concentration polarisation. Shown in figure 2 are the ideal and actual voltages of a PEM fuel cell and the region at which each of the three polarisation losses dominates [3].

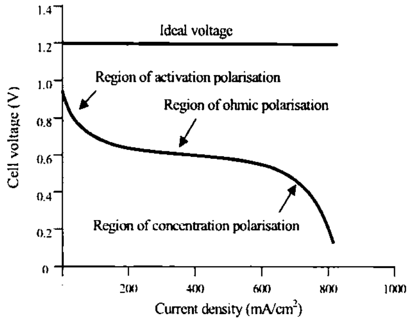

Figure 2 Ideal and Actual Polarisation Curves [2, 3]

2.3 Fuel Cell Stack

The practical working voltage of a PEM fuel cell is typically around 0.7 volts [2], and for this reason many cells may be connected in series in order to produce a higher working voltage. Bipolar plates are used to connect the fuel cells in series and also serve to supply the fuel and oxidant to the anode and cathode electrodes. Good electrical connections between the alternative electrodes of each fuel cell are maintained through the bipolar plates, and the resulting structure is referred to as a fuel cell stack as shown in figure 3.

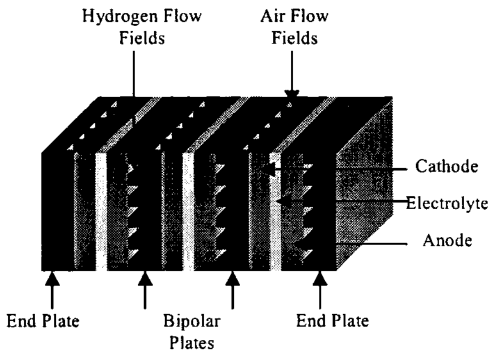

Figure 3 PEM Fuel Cell Stack [2]

2.4 Fuel Cell System

In addition to the fuel cell stack other components are required when designing a complete PEM fuel cell system. The fuel cell stack needs to be provided with clean fuel and oxidant, and the heat and the depleted reactants need to be removed. The dc power that is produced usually requires power conditioning. These processes also need to be controlled and monitored by a control system [3]. A block diagram of a PEM fuel cell system is shown in figure 4.

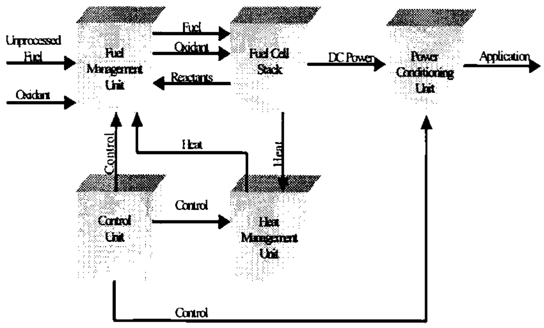

Figure 4 PEM Fuel Cell System

3. DESIGN REQUIREMENTS

PEM fuel cell models are typically used to predict the polarisation curve of a PEM fuel cell over a range of different operating conditions. The models can be empirically or analytically based, in either case experimental data is required. In the empirical models the experimental data is used to derive the performance equations. In the analytical models the experimental data is used to determine model parameters and validate the model [4].

3.1 500 W PEM Fuel Cell Stack

The specification of a 500 W PEM fuel cell stack used in the design analysis is shown in table 1 [5]. Standard Litres (SL) are used for the mass flow rates.

Table 1 500 W PEM Fuel Cell Stack [5]

Stack Power	500 W
Number of Cells	32
Nominal Voltage	19 V
Nominal Current	26.3 A
Operating Current	0-30 A
Operating Temperature	25-65 °C
Fuel	Hydrogen
Oxidant	Air/Oxygen
Hydrogen Stoichiometry	1-1.2
Hydrogen mass flow	0-8.0 SL/min
Hydrogen inlet pressure	0-5 PSI
Air Stoichiometry	2-2.5
Air mass flow	0-42.14 SL/min
Air inlet pressure	1-202KPa PSI
Air cooling operation range	0–100 (<150) W
Water cooling operation range	0–500 W

3.2 Critical Parameters

For the design of an effective PEM fuel cell test system the critical parameters that influence the PEM fuel cell stack performance must be determined. The PEM fuel cell test system is required to be able to measure and/or control these parameters. The critical parameters for the PEM fuel cell are the temperature, pressure, flow rate, and relative humidity of the reactant gases, and the temperature, voltage, and current of the PEM fuel cell stack [2, 5, 6].

3.3 Critical Parameter Specification

A summary of the critical parameter specification is shown in table 2. The analysis for the critical parameters is contained in the following sections.

Table 2 Critical Parameters

Parameter	Range
Stack Power	12-500 W
Stack Temperature	25-80 °C
Stack Voltage	5-50 V
Stack Current (Max.)	0.24-50 A
H_2 Mass Flow	0.2-10 $SL.min.^{-1}$
H_2 Temperature	25-80 °C
H_2 Pressure	100-400 KPa
H_2 Relative Humidity	5-95 %
Air Mass Flow	1-50 $SL.min.^{-1}$
Air Temperature	25-80 °C
Air Pressure	100-400 KPa
Air Relative Humidity	5-95 %

3.3.1 Stack Power

The maximum power capability of the PEM fuel cell test system is 500 W. This power capability is sufficiently large for the practical testing of PEM fuel cell stacks because of their modular design. The minimum power capability of the test system is limited by the minimum resolution of the mass flow controllers which is 2% of full range [7]. In this case, the minimum power demand of the PEM fuel cell test system is 12 W (see section 3.3.3).

3.3.2 Stack Voltage and Current

It is assumed for the PEM fuel cell test system that the maximum number of cells in a 500 W fuel cell stack is not greater than 32 or less than 10. The maximum stack voltage is set at 50 V to provide additional allowance in the maximum number of cells. For 10 cells operating at the minimum cell voltage of 0.5 V, the minimum stack voltage is 5 V. For a minimum voltage of 5 V the maximum stack current is calculated at 100 A. The minimum stack current and voltage are not critical parameters as the resolution of the measurement exceeds the minimum requirements.

3.3.3 Mass Flow Rates

At this stage air is used as the oxidant for the PEM fuel cell stack although further work may require the use of oxygen. The maximum mass flow rates are calculated at the maximum power demand, maximum stoichiometric ratios, and the minimum cell voltage. The maximum stoichiometric ratios are determined from the specification of the 500 W PEM fuel cell. The minimum cell voltage is 0.5 V because any voltage below this value may result in deterioration of the PEM fuel cell stack [6].

The maximum mass flow rates of hydrogen and air in standard litres per minute are expressed in (4) and (5) respectively, and the value of 0.21 in (5) refers to the ratio of oxygen in air [2, 6].

$$\dot{m}_{H2} = \frac{P_e \times \lambda_{H2} \times V_M \times 60}{n \times F \times V_c} = \frac{500 \times 1.2 \times 22.414 \times 60}{2 \times F \times 0.5} = 8.36 SL\,min^{-1} \quad (4)$$

$$\dot{m}_{AIR} = \frac{P_e \times \lambda_{AIR} \times V_M \times 60}{0.21 \times n \times F \times V_c} = \frac{500 \times 2.5 \times 22.414 \times 60}{0.21 \times 4 \times F \times 0.5} = 41.48 SL\,min^{-1} \quad (5)$$

These values are in close agreement with the mass flow rates specified in section 3.1. For sizing the mass flow controllers these values were rounded up to 10 $SLmin^{-1}$ for hydrogen and 50 $SLmin^{-1}$ for air.

The operating range of the mass flow controllers used in the test system is 2-100 % [7]. Therefore the minimum mass flow rate is 0.2 $SLmin^{-1}$ for hydrogen and 1 $Lmin^{-1}$for air. The minimum power capability of the test system can be calculated by substituting the minimum mass flow rate of hydrogen into (4) and rearranging the terms. The minimum power demand of the PEM fuel cell test system is calculated at 12 W.

3.3.4 Temperature

The maximum operating temperature of most PEM fuel cells is around 60-80 °C [3, 7]. The temperature range for the 500 W PEM fuel cell is 25 °C (ambient) to 65 °C [5]. To provide flexibility, a maximum operating temperature of 80 °C is specified for the fuel cell test system. The added complexity of cooling the stack below ambient temperature is not considered practical in this case and a minimum operating temperature of 25 °C (ambient) is specified. This also implies that the temperature range of the reactant gases and coolant water needs to be 25-80 °C.

3.3.5 Pressure

The maximum operating pressure for the low pressure PEM fuel cells is around 400 KPa. The maximum pressure of the 500 W PEM fuel cell is 134 KPa at the hydrogen inlet and 200 KPa at the air inlet [5]. To provide flexibility in the fuel cell test system the maximum pressure available at both the hydrogen and air inlet is 400 KPa. The minimum pressure at the inlets to the fuel cell stack is 100 KPa (atmospheric pressure).

3.3.6 Relative Humidity

The relative humidity of the reactant gases affects the performance of PEM fuel cells. This is because the PEM must be hydrated at all times to ensure the conduction of protons. If the PEM is under hydrated performance of the fuel cell stack is compromised and deterioration of PEM results. Non optimal operation also occurs with flooding of the PEM fuel cell stack.

The 500 W PEM fuel cell specified in section 3.1 is self humidified and in theory does not require humidification of the reactant gases. However humidification is included in this design because,

- It provides flexibility for the testing of non humidified PEM fuel cells,
- The humidity of the reactant gases is required for the PEM fuel cell models, and
- The safe humidity operating range for the self humidified stack is uncertain.

Relative humidity sensors typically can measure from 5-95 % relative humidity, and this is the range specified for the reactant gases.

4. SYSTEM DESIGN

The 500 W PEM fuel cell test system is designed to meet the requirements of the critical parameters specified in table 2. A description of the test system design in relation to the major functional aspects is outlined in the following sections.

4.1 Hydrogen Supply

The test system is responsible for supplying hydrogen to the PEM fuel cell stack at the specified operating conditions. In general the hydrogen will be dead ended in the fuel cell stack although allowance needs to be made for removing any unused hydrogen if venting is required.

The hydrogen is supplied from a G sized (48 SL of water) compressed tank and is 99.5 % pure hydrogen. The tank contains 6 m^3 of hydrogen at standard temperature and pressure, and this is compressed to a pressure of 13,700 KPa [8]. The tank is capable of providing 10 $SLmin^{-1}$ of hydrogen for a period of 10 hours. A two stage regulator is used to reduce the pressure of the compressed hydrogen to a reasonable value of less than 500 KPa.

The hydrogen is then filtered as a safety precaution and transported to a mass flow controller. The mass flow controller can measure and control the flow rate of hydrogen electronically by adjusting two set points [7].

The humidification of the hydrogen is probably one of the most complex aspects of the fuel cell test system design. This is largely because the humidification is non-linearly dependent on the temperature and the heating element must operate well below the hydrogen auto-ignition temperature (571 °C) [8]. For this design a commercial humidification and heating device is used. The maximum temperature of this device is 200 °C and an additional input for the required water is controlled with this device. The device can be controlled electronically by adjusting set points [7].

The pressure of the humidified and heated hydrogen is measured electronically and a manual pressure regulator is installed to limit the maximum pressure of hydrogen available to the PEM Fuel Cell Stack. The hydrogen can be electronically controlled to, bypass the fuel cell stack, or supply the fuel cell stack in dead ended mode, or supply the fuel cell stack and allow venting of unused hydrogen to achieve higher stoichiometric ratios.

4.2 Air Supply

The test system is responsible for supplying air to the PEM fuel cell stack at the specified operating conditions. An oil free air compressor is used to provide the air to the fuel cell stack at the maximum flow rate of 50 $SLmin^{-1}$ and at a regulated maximum pressure of 500 KPa [9]. Similarly to the hydrogen supply, the air is then filtered as a safety precaution and transported to a mass flow controller.

The humidification of the air is performed using a simple evaporation system. This is because the heating requirements are less stringent, and the relative humidity of air is less critical to the performance of the stack. The temperature is controlled electronically and the mass flow of water used for humidification is controlled manually. Relative humidity and temperature transducers are used to measure these parameters at the fuel cell stack input electronically.

The pressure of the humidified and heated air is measured electronically and a manual pressure regulator is installed to limit the maximum pressure of air available to the fuel cell stack. The air can be electronically controlled to bypass the fuel cell stack, or supply the fuel cell stack and allow venting of unused air to achieve higher stoichiometric ratios. The air supply cannot be dead ended because only the oxygen is used up in the cell reaction.

4.3 Coolant Supply

The cooling supply incorporates both air cooling and water cooling. The air-cooling is forced convection cooling while the water-cooling involves the flow of distilled water through the cooling channels of the PEM fuel cell stack. For air cooling a simple blower is used to promote forced convection cooling of the stack and this can be controlled electronically. For water cooling a more complex design is required. Temperature and pressure of the cooling water is monitored and the flow of the cooling water is regulated using an oil free water pump. The mass flow rate of the coolant water is calculated in (6) [6].

$$\dot{m}_{water} = \frac{P_c \times (1.25 - V_c) \times 60}{V_c \times c_p \times \Delta T} = \frac{500 \times (1.25 - 0.5) \times 60}{0.5 \times 4184 \times 5} = 2.15 \mathrm{L\,min^{-1}} \quad (6)$$

This equation applies for when the product water leaves the fuel cell stack in vapour form which is almost always the case. The stack is operating at 500 W with a cell voltage of 0.5 V, and a 5 °C temperature rise in the coolant water is allowed. The minimum mass flow rate is not critical in this design because at the lower limit of power much of the heat will be dispersed by convection cooling.

An oil free water pump capable of supplying 2.3 $\mathrm{Lmin^{-1}}$ of distilled water at 180 KPa is used in this design [9]. Water storage and filtering are included and the differential temperature of the water is electronically measured at the inlet and outlet of the stack. The maximum pressure is manual regulated as a safety precaution and the water flow can be electronically controlled to bypass the stack. A heat exchanger is used to remove the heat from the water.

4.4 Electrical Load

An electrical load is required in order to simulate a wide variety of practical loads. The electrical load is effectively a dc-dc converter with an additional resistive load at the output. The electrical load is controlled electronically and is capable of operating in constant current mode, constant resistance mode, or as a transient load.

4.5 Safety System

In order to provide safe operating conditions the fuel cell stack and peripheral devices are housed in a vacuum chamber where hydrogen can be vented. For the case where hydrogen leakage occurs in other parts of the test system, a hydrogen sensor is used.

Nitrogen is used for purging the fuel cell stack of its fuel and air, and will occur whenever an alarm condition is raised. An alarm condition results if,

- The control system detects an error,
- An emergency button is manually operated,
- The hydrogen sensor detects a leak, or
- The electrical power is removed from the system.

4.6 Control System

The control system comprises of a PC data acquisition system that uses Labview software and is capable of measuring and controlling both analog and digital signals. There are 32 differential voltage inputs available to measure each cell of the stack. The stack voltage and current are measured with the electronic load and these are fed to the PC via RS 232. The analog inputs are used for measuring the set points of the various controllers and transducers. The analog outputs are used for controlling the mass flow controllers, temperature, and humidification. The digital outputs are used controlling solenoids valves that are distributed throughout the system and are themselves used for directing the reactant gases and liquid flow. The digital inputs are used for detecting fault conditions. All system data are logged using the Labview software and additional analysis of the test data is carried out using a combination of Labview, Excel Spreadsheet, and Matlab.

4.7 Tubing and Fittings

The tubing and fittings used throughout the test system are ¼ inch in diameter. The tubing is Fluoropolymer (Teflon coated) and has a temperature range of -40-150 °C. The fittings are stainless steel where possible or otherwise brass. In addition Teflon tape is used at each fitting to minimise the possibility of leaks [10]. Devices such as condensation traps, flash arrestors, and check valves are included in the schematic diagram of the fuel cell test system shown in figure 5.

5. FURTHER WORK

Additional features to incorporate into the fuel cell test system design include,

- Heating and cooling of the coolant water,
- Heating and cooling of the stack environment,
- Independent oxygen supply,
- Mixed fuel supply for introducing gases such as carbon dioxide, and
- Implementation of systematic software analysis tools for fuel cell testing.

The significance of each of these features is subject to the thorough testing and analysis of a range of PEM fuel cell stacks. The systematic software analysis tools will be implemented in the later testing stages.

6. DESIGN SCHEMATIC

Shown in figure 5 is the design schematic and symbol table for the 500 W PEM fuel cell test system.

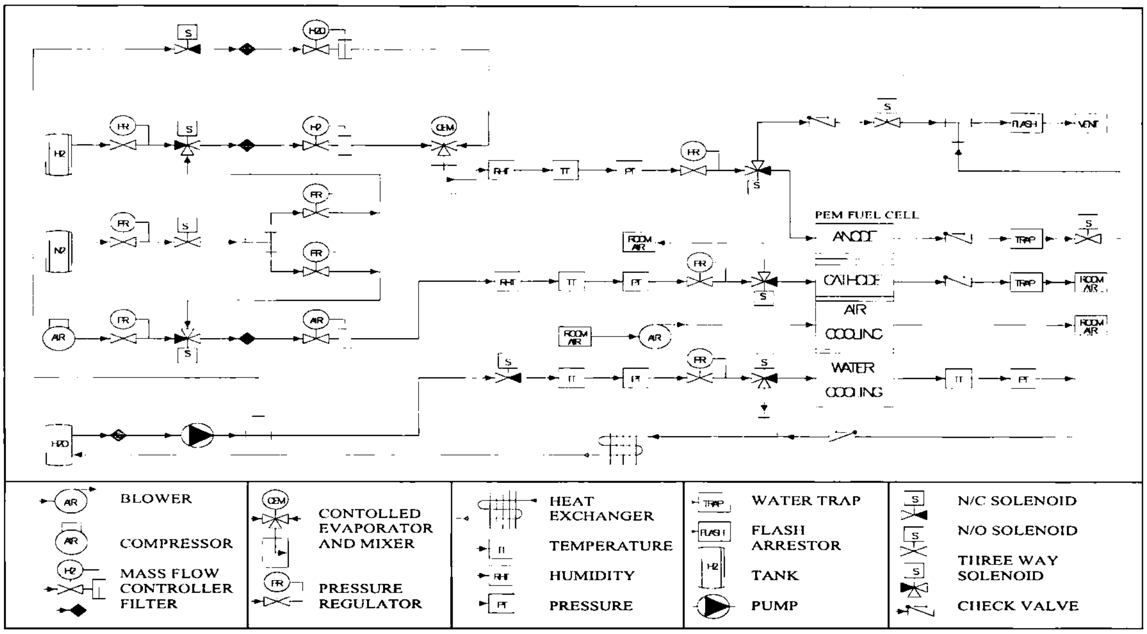

Figure 5.Schematic Diagram of Fuel Cell Test System

7. CONCLUSION

The fundamental aspects for the analysis and design of a 500 W PEM fuel cell test system are presented. The success of such a test system is dependent on the accuracy, repeatability, and simplicity of controlling the critical parameters required by the PEM fuel cell stack. In addition consideration is given for the safety of the system because of the high flammability of hydrogen. The data logging of essential parameters and software tools for analysing test data are also described.

8. ACKNOWLEDGEMENT

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9. REFERENCES

[1] K. Kordesch, G. Simader, "Fuel Cells and Their Applications", VCH, 1996.

[2] J. Larminie, and A. Dicks, "Fuel Cell Systems Explained", John Wiley and Sons, November 2000.

[3] EG&G Services Parsons, Inc., Science Applications International Corporation, "Fuel Cell Handbook Fifth Edition", National Energy Technology Laboratory, October 2000.

[4] Ø.Ulleberg, "Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems", Ph.D., Department of Thermal Energy and Hydropower, Norwegian University of Science and Technology, 1998.

[5] Forced-Flow Fuel Cell Stack (#64-32-15R), BCS Technology, Inc, Texas, Bryan, 2001.

[6] M.W.Davis, "Development and Evaluation of Test Apparatus for Fuel Cells", Masters Thesis, Virginia Polytechnic Institute State University, Virginia, 2000.

[7] El-Flow Thermal Mass Flow Controllers, and Controlled Evaporator and Mixer, Bronkhorst High-Tech, Netherlands, 2002.

[8] Industrial Grade Hydrogen (135G), BOC Gases Australia Limited, 2002.

[9] Wob-L Compressor, and Peristaltic Pump, Thomas Pumps and Compressors, Thomas Industries, 2002.

[10] Fluoropolymer Tubing and Accessories, Legris Connectic, France, 2002.

10. APPENDIX

e^-	Electron
F	Faraday's constant
H^+	Hydrogen ion
H_2	Hydrogen molecule
H_2O	Water molecule
$\dot{m}_{AIR}$	Mass flow rate of air
$\dot{m}_{H2}$	Mass flow rate of hydrogen
$\dot{m}_{H2O}$	Mass flow rate of water
n	Number of moles electrons per mole of gas
O_2	Oxygen molecule
P_e	Power produced by fuel cell stack
V_c	Cell voltage
V_M	Volume of one mole of a substance at STP
λ_{AIR}	Stoichiometric ratio of air
λ_{H2}	Stoichiometric ratio of hydrogen


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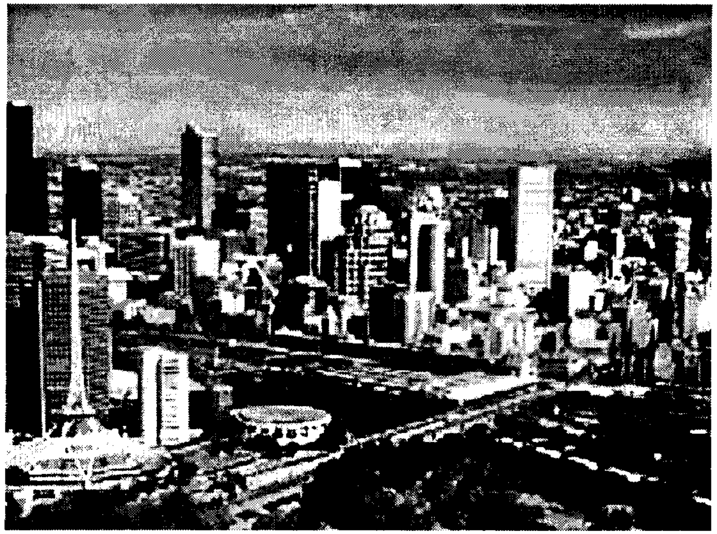

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Message from the Conference Chairman

It gives me great pleasure to welcome you all to the Australasian Universities Power Engineering Conference (AUPEC 2002). AUPEC traditionally rotates among the venues in the Australasian region and we are delighted to host the 2002 conference at Monash University, Melbourne Australia.

AUPEC is the only annual conference organised by the Australasian Committee for Power Engineering (ACPE). The primary aim of this conference is to provide a national forum for academia and industry to share innovation, development and experiences in a friendly environment. The other key aim of AUPEC is to provide postgraduate students with the opportunity to present their research findings in front of experts from both academia and industry for scholarly feedback. It also provides university academics and Industry the opportunity to interact with the technical community, to share experiences and gain the benefit from the latest developments in technology presented at the conference.

We were very pleased with the response received from our call for papers. The conference secretariat received more than 180 abstracts from prospective authors from various countries including Australia, New Zealand, Canada, Malaysia, Singapore, Japan, India, China, Finland, Egypt, Czech Republic and Iran. Members of the organizing committee selected 158 abstracts suitable for presentation at the AUPEC conference. Papers were reviewed by 60 independent reviewers from around the world. Finally, after a two-stage independent peer review process, 138 papers successfully passed the process and were accepted for presentation and discussion at the 27 technical sessions of the conference. All papers published in the conference proceedings for AUPEC 2002 have been fully refereed, having satisfied the requirements of this peer review process. My sincere thanks to all the reviewers for their time and effort toward the review process.

We are also very pleased to put forward four outstanding keynote speakers in the mornings of day one and day two of the conference.

Finally, I would like to thank all the members of the AUPEC 2002 organizing committee for their dedication and effort, without which the conference would not have been possible.

On behalf of the conference committee let me welcome you to AUPEC 2002, which is all set to be a rewarding experience in all respects.

Dr. A. Zahedi
Chairman - AUPEC 2002
29 September 2002

3. Renewable Energies and Technologies