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A fuel cell balance of plant test facility

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Abstract

Much attention is focused in the fuel cell community on the development of reliable stack technology, but to successfully exploit fuel cells, they must form part of integrated power generation systems. No universal test facilities exist to evaluate SOFC stacks and comparatively little research has been undertaken concerning the issues of the rest of the system, or balance of plant (BOP). BG, in collaboration with Eniricerche, has therefore recently designed and built a test facility to evaluate different configurations of the BOP equipment for a 1–5 kW_e solid oxide fuel cell (SOFC) stack. Within this BOP project, integrated, dynamic models have been developed. These have shown that three characteristic response times exist when the stack load is changed and that three independent control loops are required to manage the almost instantaneous change in power output from an SOFC stack, maintain the fuel utilisation and control the stack temperature. Control strategies and plant simplifications, arising from the dynamic modelling, have also been implemented in the BOP test facility. An SOFC simulator was designed and integrated into the control system of the test rig to behave as a real SOFC stack, allowing the development of control strategies without the need for a real stack. A novel combustor has been specifically designed, built and demonstrated to be capable of burning the low calorific anode exhaust gas from an SOFC using the oxygen depleted cathode stream. High temperature, low cost, shell and tube heat exchangers have been shown to be suitable for SOFC systems. Sealing of high temperature anode recirculation fans has, however, been shown to be a major issue and identified as a key area for further investigation. © 1998 BG plc. Published by Elsevier Science S.A.

Keywords: Solid oxide fuel cell; Internal reforming; Balance of plant; System study; Exhaust gas; Combustor

1. Introduction

The objectives of this study were:

- to develop a dynamic computer model of a solid oxide fuel cell (SOFC) system capable of providing data for the specification of equipment and control philosophy of an experimental test facility;
- to explore different designs and arrangements of the process equipment and to build and operate an experimental test facility to represent the balance of plant (BOP) system of an SOFC stack of 1–5 kW d.c. output.

The BOP of an SOFC carries out a number of service functions for the stack. For example, the BOP alters the fuel and air supply to the stack in response to changes in the electrical load while maintaining the inlet and outlet temperature constraints of the system, nominally set at 850 and 1050°C, respectively.

It was decided that the test rig would consist of the BOP equipment and an SOFC simulator (i.e. a simulated SOFC stack) which, together, would model the behaviour of a real natural gas fuelled SOFC system. The scale of the test rig was designed to be equivalent to a 5 kW_e system. The stack was assumed to be internal reforming.

The test rig was designed to explore the design and operation of the BOP equipment needed to carry out a number of the above service functions for the stack for a fuel utilisation per pass of 85%, which corresponded to the standard design conditions of the BOP. The SOFC simulator (see Section 3.2) was, as practically as possible, designed to behave like a real stack.

2. Computer modelling investigations

2.1. Introduction

Computer models were developed and extensively used throughout the project to:

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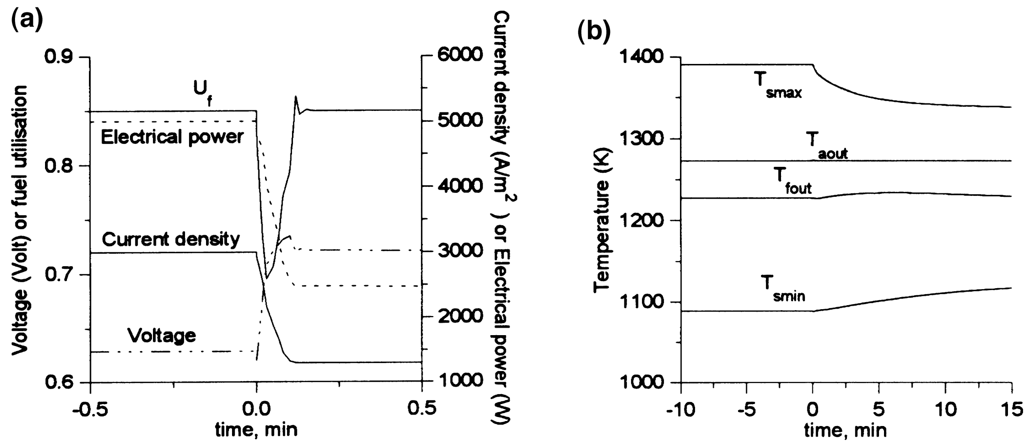

Fig. 1. Load change from 5 to 2.5 kW: variation of the stack variables with time. (a) Electrical parameters, (b) thermal parameters, T_{smax} = maximum solid temperature, T_{aout} = outlet air temperature, T_{fout} = outlet fuel temperature, T_{smin} = minimum solid temperature.

- investigate the process dynamics of the BOP for an SOFC system;
- provide data for the specification of equipment;
- produce a greatly improved understanding of the stack/BOP interactions;
- explore and specify control strategies for the experimental test facility;
- study the effect of start-up and load variation on the stack.

2.2. Steady state SOFC stack modelling

2.2.1. SOFC stack modelling

Steady state stack modelling work carried out by Eniricerche, using an 'in-house' code, was able to produce realistic information on the behaviour of a 5 kW_e SOFC stack with internal reforming and anode recycle. This model was used to define the boundary operating conditions for a real SOFC stack. One of the results of this work indicated that thermal stresses could severely limit the permissible temperature rise across the stack; this constrained the upper value of the fuel utilisation per pass and allowed BG to set appropriate limits to the design and operation of the BOP.

The stack model was also used as a basis for developing and verifying:

- a simplified dynamic model for an internal reforming SOFC stack, to incorporate into an integrated SOFC/BOP dynamic model for an SOFC system;
- a parametric stack model for the SOFC BOP simulator.

2.3. Dynamic modelling

2.3.1. Stack model

Starting from the steady state model, a dynamic stack simulator was developed by ER and was used to study the start-up and the changes of the stack load during operation. For example, in Fig. 1, the time variation of the electrical and thermal variables during a load change from 5 to 2.5 kW are shown. Three characteristic stack response times were identified: power converter, ~0.1 s; fuel and oxidation rates, ~l s; and solid temperature change, 100–1000 s. This led to three independent control loops being identified. The fastest one relates to the power control circuit required to manage the almost instantaneous changes in power output from a stack in response to changes in external load. The second loop acts to maintain constant fuel utilisation by varying the fuel feed rate in response to changes in load. A third much slower loop acts to control the temperature of the stack.

2.3.2. Balance of plant model

BG developed a dynamic model to represent the BOP using SpeedUp (Aspentech), validating it against steady state simulations. Extensive work was carried out jointly by ER and BG to develop and demonstrate an integrated SOFC stack/BOP SpeedUp dynamic model. Fuel utilisation control was added to the model which was used to simulate control and plant responses to dynamic load changes, and to develop and optimise control strategies for the BOP.

3. Design, construction and operation of the test facility

3.1. Overall process design

A simplified process flow diagram (PFD) of the test facility is shown in Fig. 2. The function of the anode side of the BOP is to manage and condition the fuel supply for optimum operation of the anode of an SOFC. Natural gas enters the plant and is preheated to 350°C prior to desulphurisation. The desulphurised stream then enters the anode recycle loop prior to a prereformer. After prereforming, the fuel stream is heated in a heat exchanger and then a trim heater before entering the anode simulator section of the plant. Part of the gas exiting the simulator is passed to the combustor while the remainder is recycled. An air cooler protects the anode recirculation fan from excessive temperatures.

On the cathode side, incoming cold air passes directly into the cathode recycle loop and is mixed with recycled oxygen depleted air from the cathode recirculation fan, prior to passing through a heat exchanger and a trim heater before entering the cathode simulator section of the plant. The cathode exhaust gas is also cooled (heating the cathode feed stream) to protect the cathode recirculation fan from excessive temperatures. The cathode exhaust stream is then split with a portion being recycled and the remainder being passed to the combustor. A bypass of cathode exhaust gas around the combustor ensures good management of the combustion process. The bypassed gas is mixed with the combustion products which provide the preheat for the incoming fuel stream. The spent gas is then vented.

The BOP test rig (Fig. 3) was constructed by BG at the Gas Research and Technology Centre.

3.2. SOFC simulator

As a real SOFC stack was not available to incorporate into the BOP, an SOFC simulator was designed for the test rig. The simulator was designed to:

- provide anode and cathode product gases which, as closely as possible, match the composition, temperature and flowrate of the product gases from a real SOFC stack;
- simulate the electrical power and waste heat produced by an SOFC stack under both steady state and transient operating conditions;
- simulate the performance of an SOFC stack during start-up, shutdown, hot hold and load change;
- represent a 5 kW_e system.

A number of techniques, conceptual designs and technologies for the SOFC simulator were investigated. A simplified schematic diagram of the simulator as built is shown in Fig. 4.

A simulator mathematical model, developed by BG, determines the output conditions from an SOFC based on the actual inlet conditions and operator defined values for power output and fuel utilisation. Dynamic data exchange between the model and the advanced process automation and control system of the BOP results in the automatic and real time setting of flow controllers and process heaters to mimic the outlet gas compositions from an SOFC.

3.3. Exhaust gas combustor

The exhaust gas from the anode of an SOFC is discharged at elevated temperatures as a lean gas, containing a high proportion of steam, and having a calorific value of ~10%

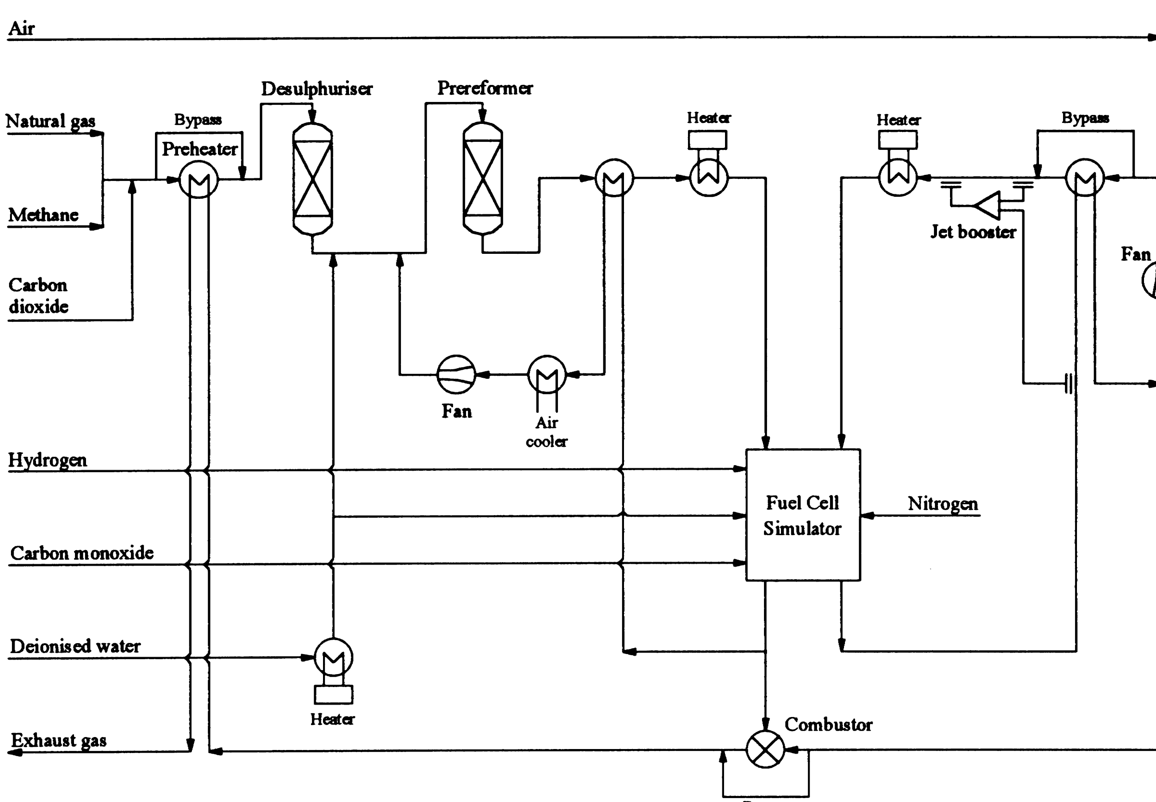

Fig. 2. Simplified schematic PFD of the BOP.

of the natural gas fuel. The cathode exhaust stream comprises of oxygen depleted air and it was not known under what conditions the anode exhaust gas could be completely combusted using the cathode exhaust gas as oxidant. Extensive computer modelling and design was carried out before a prototype combustor was built and tested to aid with the development of the BOP combustor. This has been described elsewhere [1].

Tests have shown that the BG designed non-catalytic combustor is capable of burning anode exhaust gas from an SOFC using the oxygen depleted cathode stream corresponding to full recycle mode of operation. Stepwise introduction of flammable gases indicated that the combustor works over a range of compositions of anode exhaust gas and will operate on a fuel gas which is much leaner than the standard design composition.

3.4. Electrical process heaters

The function of the electrical heaters of the BOP are three-fold:

- to heat the process gas streams to the fuel cell simulator to the operating temperature;
- to simulate the temperature rise that would occur across a fuel cell stack;
- to compensate for system heat losses.

All process heaters on the BOP are induction heaters. Considerable problems were experienced with the induction heaters and none performed to their specified design, though modification meant that they were adequate for operation on the BOP.

Experience in building the BOP demonstrates the impor-

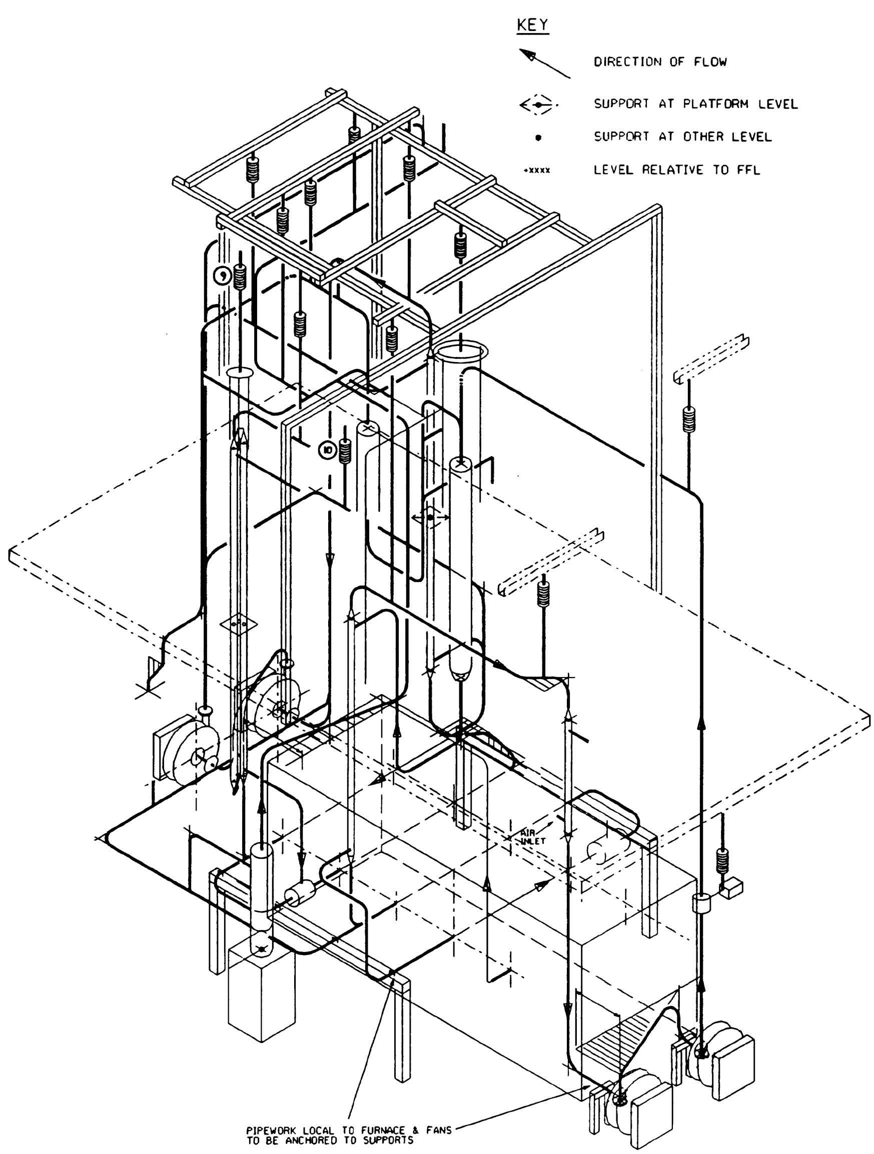

Fig. 3. Layout of the pipework support structure of the BOP.

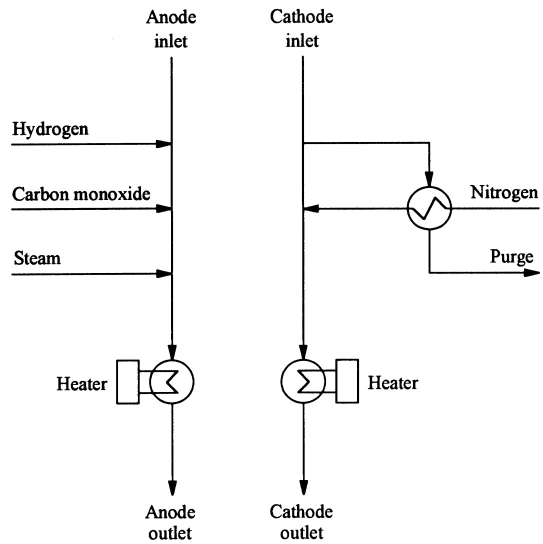

Fig. 4. Simplified schematic of the simulator.

tance of building and operating real systems in order to obtain knowledge of the important issues that cannot be gained from process and system studies alone.

3.5. Recirculation fans

The design temperature for the anode recirculation fan is 450°C and for the cathode recirculation fan 375°C. Each fan was required to overcome a relatively high pressure drop with relatively small process gas flowrates. This combination of process requirements is particularly difficult to meet but, after due consideration, a double impeller twin fan design was selected for both the anode and the cathode recirculation fans. These fans were considerably oversized for the scale of operation of the BOP, being capable of 50 times the design flowrate. They were, nevertheless, able to operate at the designed flowrates for the BOP test facility.

The operating temperature of the anode fan and the requirement that no combustible gases could leak into the laboratory led to the design of a special purged seal, operating at 400°C. Even with this some leakage did occur with anode recycle. This implies that a new design of seal will be required for high temperature duty in future SOFC systems of this type.

3.6. Desulphurisation vessels and pre-reformer

Several options for desulphurisation of the fuel gas were considered with the chosen system being based upon the proprietary ICI Katalco Puraspec™ catalyst (PURAPSEC™ is a trademark of ICI Chemicals and Polymers Ltd. Puraspec Purification Processes, ICI Katalco, Billingham, Cleveland, UK).

A prereformer was included in the plant design to remove higher hydrocarbons from the natural gas feed. To eliminate the need for an external steam supply for the prereformer, it was positioned in the anode recycle loop to utilise the steam in the recycle (for single pass operation, steam is diverted from the SOFC simulator). This prereformer was designed to operate with a very low pressure drop, to enable the recirculation fan to achieve the flowrates required, and to operate adiabatically with an inlet temperature in the range 400–450°C.

3.7. Heat loss from the process

The relatively small scale of the BOP (1-5 kW_e) meant that moderate absolute losses of heat from the process could lead to large reductions in the process gas temperature. Including allowances for efficient ceramic lagging, the losses are great enough to warrant the use of electrical heat tracing. Even with such measures, initial commissioning tests showed that heat losses, particularly on the anode recycle loop and especially around the recirculation fan, were too great, resulting in condensation of steam in the recycle loop.

The trace heating on the anode side of plant was, therefore, upgraded. This consisted of increasing the total power to the heating elements, and applying the heating elements directly to process pipe and the casing of the anode fan. The upgrade allowed the plant to be commissioned with no steam condensation, in the anode recycle loop.

3.8. Heat exchangers

The BOP heat exchangers are simply a single pass tube in tube design which enables the heat exchangers to be sealed to any desirable size. The heat exchangers throughout the BOP exceeded their design specifications with the stream being cooled and exiting the exchangers at lower temperatures than design. This contributed to operational problems ex-perienced on the anode side of the plant

Although not theoretically required, inclusion of an anode recycle heat exchanger bypass would allow fuller control and flexibility of the BOP.

3.9. Flow measurement

All flow measurement on the BOP is achieved using orifice flow elements. This method was selected because it was the most suitable, and had the lowest costs, for use in the high temperature regions of the plant and, consequently, was adopted as standard for the BOP. One design criteria for the BOP was that pressure drops should be minimised and this led to the use of large diameter (in relation to the pipe diameter) orifices. For operation at standard design conditions, measured flowrates were consistent. However, inconsistencies in the measurement of flow around the plant did occur, being most significant at low flowrates. The inconsistencies arose largely as a result of the demands placed upon the orifices, which are not designed to cope with large turn down ratios.

One objective of the project was to investigate methods to simplify an SOFC BOP, in terms of equipment and operation, and the practical experience gained with flow measurement systems demonstrates that this could be done by moving away from conventional flow measurement for control. One area of the plant suitable for simplification is the method of recycle flow control and this led to system control modifications (see Section 3.11).

3.10. Cathode air flow control

A practical implication of the dynamic modelling work was that the operating temperature of an SOFC stack could be moderated using the cathode gas flowrate without significantly affecting the other important operating parameters of a stack. To test this, a control loop was configured and tested in the control system to vary the cathode air flowrate in response to the anode outlet temperature and its operator defined set-point. In addition to the basic controller, a fail-safe check was incorporated to ensure that the controller could not demand a flowrate that would provide less than the stoichiometric oxygen demand of the electrochemical reactions of an SOFC plus a predefined safety margin.

3.11. Recycle flow control

Two methods of flow control were provided for both the anode and cathode recycle loops (i.e. a variable position valve and variable speed drives to the recirculation fans) to investigate means to simplify the design and operation of an SOFC BOP, and to reduce the capital cost of the BOP. Although flow control valves were expected to control recycle flows adequately, it was not known whether the operating characteristics of the low throughput, fans would allow stable control of recycle flowrate. Experiments were conducted to investigate the viability of flow control by each method.

It was found that on the anode recycle loop, both the control valve position and variation of the fan speed adequately controlled the recycle flowrate with good stability. Control loops for each method of flow control were configured for the anode and were tuned to give the option of using either method during plant operation.

On the cathode recycle loop, the characteristics of the particular variable position valve meant that fan speed control was the only method that gave stable flow control. Consequently, only one recycle flow controller, based on recirculation fan speed, was configured and tuned for the cathode recycle loop.

This research has demonstrated that recycle flowrates can be adequately controlled by utilising variable speed drives to the recirculation fans and this method can replace conventional flow measurement and flow control valves, thereby simplifying the design and operation of a BOP.

3.12. Automatic operation

An objective of this study was to demonstrate automatic operation of an SOFC BOP system by devising and programming into the control system automatic operating sequences. Progress towards the final automatic operating sequence was made in stages. Two of the sequences developed and tested were.

1. Combustor pilot light sequence. This sequence allows an operator to activate the pilot light of the combustor via the graphical interface of the control system. The sequence included the opening of flow regulating valves (natural gas and air), operation of the ignition transformer, and the monitoring and detection of a flame.
2. Automated warm-up sequence. The system was programmed to bring the plant up to operating temperature in discrete stages.

4. Conclusions

Integrated, dynamic models of SOFC systems have been developed and demonstrated to be powerful tools for devising improvements and simplifications to the design and control strategy of SOFC systems.

Dynamic modelling has shown that three characteristic response times exist when the stack load is changed and that three independent control loops are required to: manage the almost instantaneous change in power output from an SOFC stack, maintain the fuel utilisation and control the stack temperature.

A 1–5 kW_e SOFC BOP test facility has been built and control strategies and plant simplifications, developed from dynamic modelling investigations, have been implemented.

An SOFC simulator has been designed and integrated into the control system of the test rig to behave as a real SOFC stack, allowing the development of control strategies without the need for a real stack.

A novel combustor has been specifically designed, built and demonstrated to be capable of burning the low calorific anode exhaust gas from an SOFC using the oxygen depleted cathode stream.

High temperature, low cost, shell and tube heat exchangers have been shown to be suitable for SOFC systems.

Sealing of high temperature anode recirculation fans has been shown to be a major issue and identified as a key area for further investigation.

The SOFC BOP test facility has been commissioned and is now able to provide a platform for the testing and benchmarking of kW scale SOFC stacks in a real system environment.

Acknowledgements

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Reference

[1] R. Hicks, *Young Engineer Paper presented at the Institution of Gas Engineers, Midlands Session at the Gas Research Centre*, 17th January, 1996.