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Leak diagnosis of polymer electrolyte membrane fuel cell stacks

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ABSTRACT

Pressure decay test is usually used to highlight leakages inside the stack between anode, cathode and cooling compartments. Although this test can satisfactorily detect leaks occurring within the stack, it does not help in localization of the leak source in the stack. This paper presents some descriptions of two PEMFC stacks which have leakage between anode/cathode or cathode/cooling compartments. A variety of diagnosis techniques including IR thermography, Open Circuit Voltage decay, Crossover Current, Open Circuit Voltage growth are employed with the goal to locate the leak sources in the stacks. Furthermore, some techniques are presented to find the leak types and sources in the defective cells in the stack. Since hydrogen and air are not used simultaneously in the stack, the crossover current test is safer than the other methods. However, results of this test are strongly dependent on the nitrogen flow rate. The results of IR thermography show that this technique has a good potential to be used along with the other methods in the leak diagnosis of the PEMFC stacks. In fact, this technique can be used to build confidence in the results of the other leak diagnosis techniques.
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Introduction

Despite of wide researches and progressions on the fuel cells, several technical barriers to their commercialization still exist, especially about their durability and cost [1–3]. The durability, reliability, and ultimate cost of a polymer electrolyte membrane (PEM) fuel cell (PEMFC) stack are the direct results of the repeating elements used in its construction. PEM fuel cell stacks are generally comprised of two or three independent circuits, a fuel (anode) circuit, an oxidant (cathode) circuit and if the stack is liquid cooled, a coolant circuit. Each of these circuits has the potential to leak either externally, or into one of the other circuits. There are a number of reasons that leaks may occur in a fuel cell including: faulty components, seal failures, membrane electrode assembly (MEA) failure, stack misalignment and lack of tightness [4–6].

The leak diagnosis tests may be carried out in two cases: 1-at stack beginning of life after the assembly, before any use of hydrogen and any electrical performance test for quality assurance of the stack components and the assembly process,

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2- when a leak between the Hydrogen/Air/Cooling compartments or an unusual behavior is observed in an aged stack.

Pressure tests performed with nitrogen or helium are usually employed to highlight gas leakages inside the stack between the anode, cathode and the cooling compartments [7]. These tests are designed to detect faulty stack components, for instance broken MEA or defective sealing, and stack assembly faults like displaced gaskets [8]. Even though these procedures allow perfectly well the detection of leaks occurring within the stack assembly, they are not appropriate to locate which cell or cells have failed, and to inform where the fault has occurred.

Generally, in the literature, there are a limited number of researches on the localization of leaks in PEM fuel cell stacks. These researches are mainly based on leak diagnosis using the method of monitoring of cell open circuit voltages (OCV) during the processes in which pressure difference between the anode and the cathode sides fluctuates or some transient shut-off of the reactive gases are applied. In Ref. [8], a test procedure allowing the failed cells to be detected was described. The procedure was applied to a three cell PEMFC. Basically, the technique consisted in feeding the stack with H_2 and air during 10 s, and then shutting off the gas flows suddenly. By shutting-off the reactants supply, the OCV of cells started to decrease at different rates. While the OCV of normal cells did not change considerably, the voltage of cells with crossover leak showed a noticeable drop after the shutting-off the gases. The quick decrease of the potentials can be explained by the rapid hydrogen consumption in the anode electrodes, which leads to fast decreases of the H_2 partial pressures available at the reaction interfaces. The H_2 consumptions at the anodes may have different causes: fuel crossover through a membrane break or hole or leak through a damaged sealing [8]. Tian et al. carried out some experimental investigations with the goal to locate the defective cells in a stack [9]. In their work, the OCV of cells were monitored and analyzed in different operating conditions. They used experimental procedures combined with data analysis tools to detect the failed cells. Khorasani et al. used the method of monitoring of OCVs during fluctuations of pressure differences between the anode and the cathode sides to determine the failed cells in their 5 cell and 18 cell stacks [10].

Although localization of leaks in a stack assembly using the OCV decay technique is of some interests, but it suffers from some difficulties in interpretation of the test results and detecting the exact location of leak in the stack, especially in the cases where amount of leakage in the defected cells is not high enough to cause high and rapid voltage drops. This is due to the fact that the rate of voltage drop after shutting-off the gas supply in the OCV decay test depends not only on the membrane/sealing defects but also on cell positions in the stack, the stack internal design, the position of the gas inlets–outlets in the stack, ... Therefore, besides OCV decay test, alternative experimental diagnosis test methods are needed to build confidence in the test results. To our knowledge, there have been no studies which have used other methods besides the OCV decay test in leak diagnosis of PEMFC stacks in order to build a comparison between the test results. However, there are some studies which have used some techniques other than the OCV decay in the leak diagnosis of single cells. But it should be mentioned that the diagnosis problem is quite different in an FC stack which composed of numerous cells. For example, Inaba et al. evaluated the hydrogen crossover rate in a single cell using the linear sweep voltammetry [11]. Mousa et al. used electrochemical impedance spectroscopy (EIS) to detect hydrogen leaks and oxygen concentrations in a single cell [12].

The IR thermography has been used by some researchers to reveal the defects in PEM single cell and fuel cell components. This method has been employed for detecting catalyst-loading defects in the fuel cell gas diffusion electrodes [13] and investigating the degradation mechanisms as an ex situ diagnostic tool [14]. Bender et al. developed a single cell hardware and methodology for spatial detection of pinholes and failure points in a PEMFC single cell [15]. The system was based on performing infrared thermography on crossover hydrogen reacting with ambient air. It seems that the infrared thermography technique may have a great potential in leak diagnosis in a fuel cell stack. To our knowledge, there have been no reports regarding leak diagnosis of PEM fuel cell stacks using infrared thermography technique. We have used this technique in our investigations besides the other techniques to examine its usefulness.

Another important matter in the leak diagnosis of the fuel cell stacks is finding the leak locations and sources in the cells where diagnostic tests have shown that the leak in the stack originates from them. Generally, there may be different leak sources and locations in a cell with leak. For example, there may be different possibilities of leak locations in a cell which has an anode/cathode crossover leak, like: anode/cathode crossover through the membrane, leak from the anode inlet or outlet manifolds to the cathode flow field due to gasket defects, leak from the cathode inlet or outlet manifolds to the anode flow field due to sealing failure. Finding of the leak location in a cell can help to easily discover the fault resulted in leak in the defected cell. Therefore, developing some supplementary test methods to find leak cause and location in a defected cell in a PEMFC stack can be very helpful. This issue has not been addressed in the literature yet.

In the present research, different leak diagnosis tests are carried out on two stacks at their beginning of life, after the assembly process with the goal to locate the leakage source in them. The collected test results are commented and analyzed. Briefly, the objective of the present research is to investigate direct, simple and safe methods allowing the detection of the cells with leak in a PEM fuel cell stack in conditions that maintain as much as possible the integrity of the other safe cells. In addition, some test procedures for finding the leak location and source in the defected cells are developed and described.

Different types of leak in a PEM fuel cell stack

There are two main categories of leakage within a PEM fuel cell stack: anode/cathode crossover and leakage between anode and/or cathode and cooling compartments. The crossover leakage is when the gas from one side of the membrane crosses over to the other side of the membrane. A crossover leakage can occur in two ways: one is a leak between the

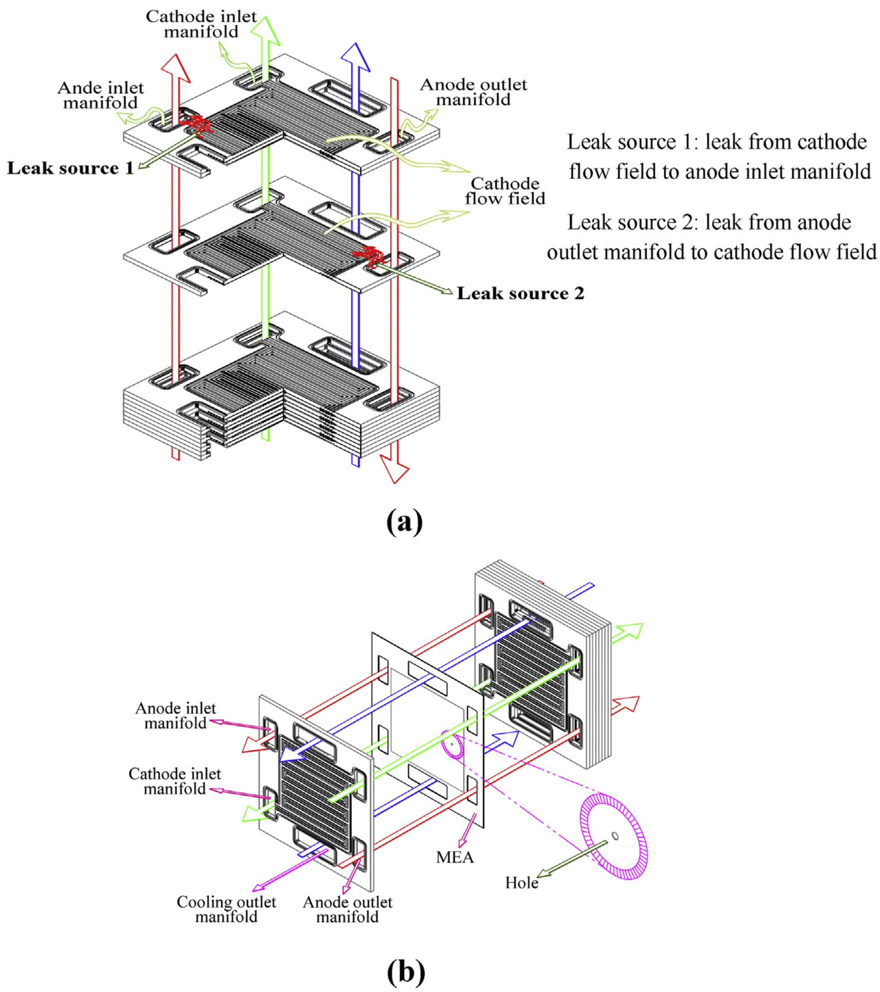

Fig. 1 – Different ways of anode/cathode crossover leakage; (a) leak between the gasket and the membrane in the inlet or outlet ports; (b) leakage by passing through the membrane itself.

gasket and the membrane in the inlet or outlet ports (Fig. 1a) and the other is by passing through the membrane itself (Fig. 1b). There is an expected crossover leak rate of hydrogen and oxygen through the membrane due to diffusion which can be estimated for any given stack based on the number of cells in the stack, active area, and type and thickness of the membrane assuming that the seals are perfect [5].

The leak between anode and/or cathode and cooling compartments occurs in two ways assuming that bipolar plates are perfect: one is leak between cooling flow fields and gas manifolds (leak source 1 in Fig. 2) and the other one is a leak between gas flow fields and cooling manifolds (leak source 2 in Fig. 2). This type of leak is mainly caused by gasket failure, stack misalignment and lack of tightness.

Experimental

Pressure decay test and electrical insulation test are the two tests that are generally carried out after the stack assembly and before conditioning. In our case, some pressure decay tests were performed on four stacks after the assembly process to reveal any eventual leak. The results of pressure decay tests indicated that among these four stacks, two of them had leaks between compartments. The aim of the present study is to locate the leakage source in these two stacks. These home-made stacks (Fig. 3) have the same specifications. They are of water-cooled type with three separate hydrogen, air and cooling compartments and inlet and outlet manifolds. Each stack contains 70 cells with a cell active area equal to 225 cm^2. The MEAs consist of NRE-211 membrane, catalyst layer with a total Pt loading of 0.4 mg cm^{-2} at both the anode and cathode sides and SGL carbon cloth with micro porous layer as the gas diffusion layer (GDL). A more detailed description of the anode and the cathode flow fields can be found in our previous work [16].

Different leak diagnosis methodologies were used to find the leak type in the stacks and also to locate the leakage source. The leak test procedure and conditions are described below.

Pressure decay test

By this test, the leak rate inside a fuel cell stack from one compartment to the other ones is assessed without the ability to locate the leakage source. In this way, one compartment of the stack is pressurized up to a set point with nitrogen or

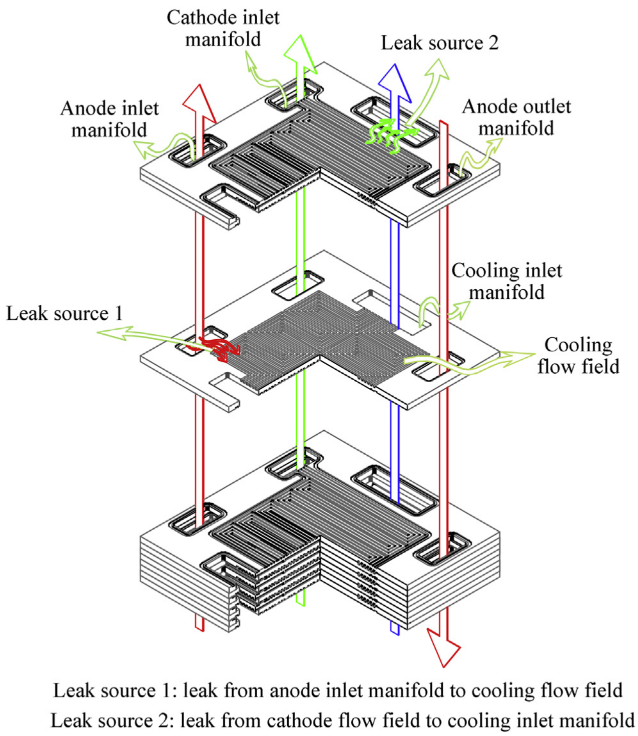

Fig. 2 – Different ways of leakage between the anode and/or the cathode and the cooling compartments.

helium (helium is preferred because it is the lightest of the inert gases, is more representative of hydrogen and it penetrates small leaks readily) and the other compartments are sealed at ambient pressure. Then, the pressures in the compartments are monitored. The leak from the pressurized compartment to the other ones can be detected by the pressure increase at the sealed compartments. The nitrogen flow at stack inlet can be measured to evaluate the leakage flow rate.

In the present research, this test was used to find if there is any leakage between different compartments in the stack. In the cases where evaluation of leakage from the anode or the cathode compartments to the other compartments was desired, the pressure set point was adjusted to 500 mbar. The pressure difference between anode and cathode should not exceed 500 mbar to prevent any damage to the MEA [8].

In the case where evaluation of leakage from cooling compartment to the anode or the cathode compartments is needed, the pressure inside the cooling compartment can be increased up to at least working pressure of anode, cathode or cooling subsystems, whichever is greater. However in this case, the maximum pressure difference of 500 mbar between anode and cathode should also be considered. In our test, the pressure set point was adjusted to 1.0 bar. The pressure difference between the anode and the cathode was monitored during the test and in the cases where its amount exceeded than 500 mbar, the test was stopped.

Fig. 3 – One of the fuel cell stacks used in the leak diagnosis tests.

OCV decay test

In this test, hydrogen was supplied to a compartment (for example, the anode side) and air was supplied to another compartment (for example, the cathode side). The OCV of individual cells was monitored. After about 1 min, when the voltages were stabilized, the hydrogen side was pressurized. The pressure difference between the hydrogen and air sides was maintained at about 0.1 bar.

By pressurizing the hydrogen side, the individual cell with crossover leak shows higher OCV drop than normal cells. The OCV of normal cells does not change considerably at a small change of pressure difference between hydrogen and air. On the other hand, the OCV of cells with crossover leak shows a noticeable drop when the hydrogen is pressurized. The diagnosis test duration with hydrogen supply shall be as short as possible. In our cases, the test duration differed from test to test. Generally, it varied between 1 and 3 min in all the tests. The duration of a specific test can be found out from voltage–time diagram of that test.

Obviously, with the use of H_2 inside a stack with leak in it, the important issue of safety for persons and materials must be taken into account.

Thermography test

As stated earlier in section Introduction, there are some researches in which infrared thermography has been used for the diagnosis of PEM single cells [13,15]. But so far as we know, it is for the first time that we employ this technique for the leak diagnosis of a PEMFC stack. The test procedure and conditions are the same as those of the OCV decay test. By pressurizing the hydrogen side, hydrogen will transfer from the hydrogen compartment to the air compartment in defective cells. Oxygen in the air side burns off the leaked hydrogen. The burning process causes heat generation. The generated heat locally increases the temperature of bipolar plates of the defective cells. These local small temperature increases can be detected by using a sensitive infrared thermal imaging camera. Obviously, the safety issues must be taken into account in this test. In addition, the test duration shall be as short as possible.

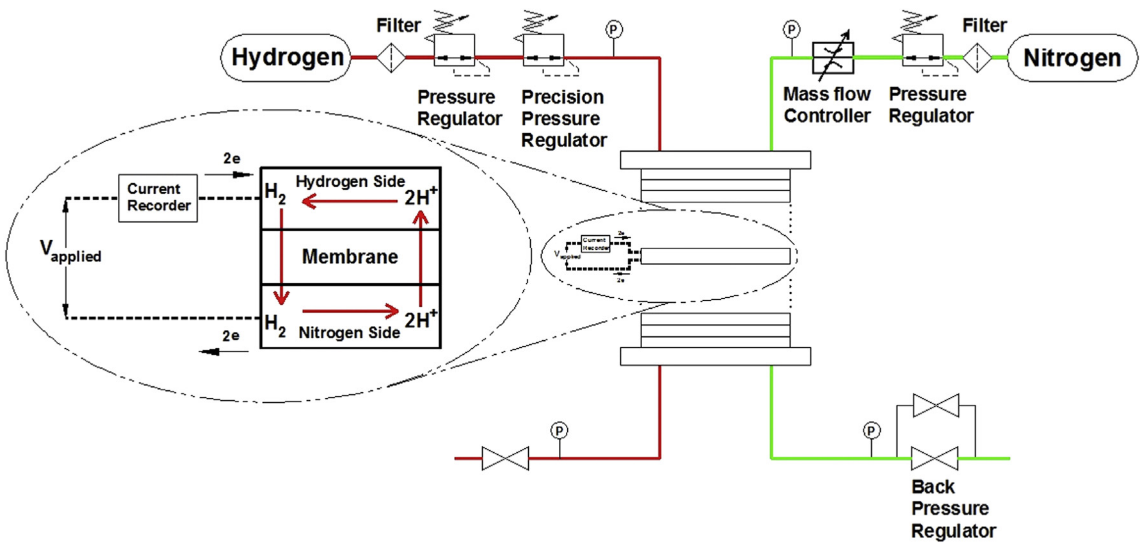

Fig. 4 – Schematic of the crossover current test and the test bench.

In the present research, thermal imaging was performed using a 640 × 512 focal plane array camera (SC5600MB FLIR, UK).

Crossover current test

This test involves delivering nitrogen to a compartment (for example, the anode side) and hydrogen to another compartment (for example, the cathode side). Hydrogen pressure is slightly higher than that of nitrogen. Any crossover leak will result in hydrogen transfer from the hydrogen compartment to the nitrogen compartment. A schematic of this test and the related test bench is shown in Fig. 4. The voltage is applied across each individual cell in the fuel cell stack and the current is measured at each individual cell with the aid of terminals normally used for cell voltage monitoring. In the cells with crossover leak, the hydrogen leaked into the nitrogen compartment is oxidized by applying the voltage and, therefore, results in a current. The applied voltage and the nitrogen flow rate have some effects on the crossover current test. For example, the crossover current is zero at the zero voltage and increases as the applied voltage increases and finally starts to level off at about 0.15 V [17]. The nitrogen flow can also affect the crossover current. High flow of nitrogen can result in low current [17]. Nitrogen flow rate needs to be optimized to obtain best sensitivity.

In the present research, the pressure difference between the hydrogen and nitrogen sides was kept at about 0.1 bar. A voltage of 0.2 V was applied through each cell. The test was performed under different nitrogen flow rates ranging from 10 to 180 SLPM to study the flow rate effect on the crossover current.

Leak testing from cooling compartment to other compartments (OCV growth test)

This test is used to locate the source of leak from cooling compartment to the anode or the cathode compartments. In this way, at first, all compartments are purged with nitrogen to remove any available oxygen. Then, for example, in the case where leak diagnosis from the cooling compartment to the cathode compartment is desired, hydrogen and air are supplied to the cooling and the anode compartments, respectively. In addition, a small flow of nitrogen is delivered into the cathode side. In our test, nitrogen was regulated to flow through the cathode at the rate of 50 SLPM. Afterward, the cooling compartment is pressurized. The hydrogen pressure in the cooling compartment can be up to 0.5 bar. The open circuit voltages of cells are simultaneously monitored. Any leakage will result in hydrogen transfer from the cooling compartment to the cathode compartment where nitrogen flows through. By this way, the OCV of the individual cell with leak from the cooling compartment to the cathode side starts to grow rapidly. It should be mentioned that after the test, all compartments should be purged with nitrogen.

Results and discussion

First stack

Pressure decay test indicated that there was a crossover leakage between the anode and the cathode compartments. Further investigations showed that there was not any leakage between the cooling and the cathode or the anode compartments. Since it was impossible to locate the leak source by the pressure decay test, other leak diagnosis tests were employed to locate the leak source.

Crossover current test for locating anode/cathode leak source

In this test, hydrogen and nitrogen were delivered to the anode and the cathode sides, respectively. Fig. 5 shows the crossover currents of cells in the stack at different nitrogen flow rates. We have presented 10 to 180 SLPM curves to show the limit of the approach and the variation of crossover current with the nitrogen flow rate. As seen from this figure,

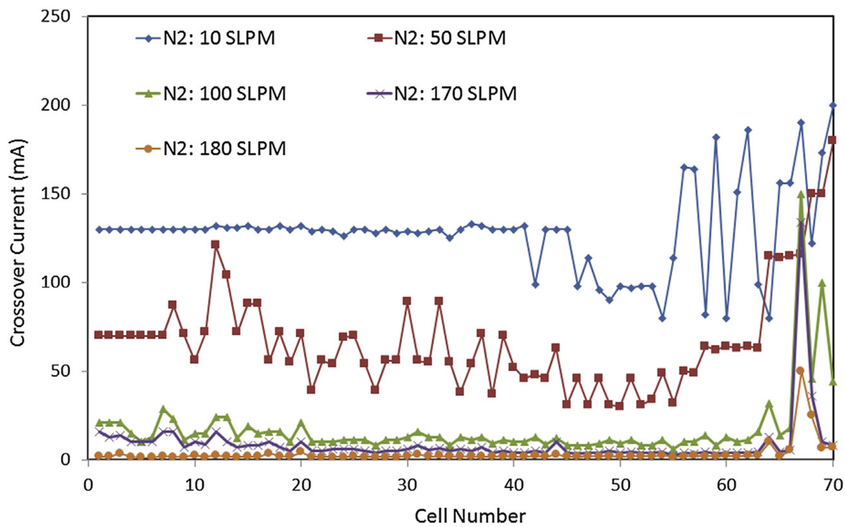

Fig. 5 – Effect of nitrogen flow on the crossover current of individual cells.

nitrogen flow rate has a considerable effect on the cell crossover current. The crossover current decreases as the nitrogen flow increases. Even though the curve related to the flow rate of 100 SLPM shows similar results with the 170 and 180 SLPM curves in most of individual cells, 100 SLPM curve shows a leakage in Cell 69 while 170 and 180 SLPM curves do not show such a leak in this cell. It is due to the fact that when the nitrogen flow rate is not as enough as required, the leaked hydrogen in the defected cell may transfer easily to the adjacent cells through the manifolds. In this way, the crossover current test shows leak in intact cells by wrong.

On the other hand, 170 and 180 SLPM give almost the same results. The diagram related to the flow rate of 180 SLPM clearly shows that Cells 67 and 64 have leak.

Now, the main question is to find the crossover leak type in these cells: leak between a damaged gasket and the membrane in the inlet or outlet manifolds or the leak by passing through a membrane break or hole? This test by itself does not give any further information on the type of the leak. Therefore, further tests are needed to find its type.

One of the solutions is carrying out the crossover current test while the hydrogen and nitrogen sides are reversed. In this test, hydrogen and nitrogen were delivered to the cathode and anode sides, respectively. The test was carried out at different nitrogen flow rates. The test results showed that the nitrogen flow rate of 180 SLPM was suitable for locating the leak source. Fig. 6 shows the comparison between crossover currents in the direct and reverse tests. As seen from this figure, in contrast to the direct test which indicates leak locations in Cells 67 and 64, the reverse test shows no leakage in the stack.

If the leak originates from any membrane hole, both tests should locate the same cells as the defected cells. Since this is not the case, some other leak source(s) should be found. The most probable source is the leak from the anode port to the cathode flow field or the leak from cathode port to the anode flow field.

For example, in the direct test, there may be some leaks from anode manifold (hydrogen side) to the cathode flow field (nitrogen side) in Cells 67 and 64. In the reverse test, in which hydrogen and nitrogen sides are reversed, these breaches in Cells 64 and 67 cause hydrogen leak from the cathode flow fields into the anode manifold where nitrogen flows. If the manifold where the hydrogen is leaked in it, is the inlet manifold, the leaked hydrogen will flow into nitrogen side of the subsequent cells (Cells 65 … 70) and will affect them. Therefore, the subsequent cells should indicate a kind of leakage. Since the crossover currents of the subsequent cells do not show such a behavior, it can be concluded that the manifold where the hydrogen is leaked in it, is the outlet manifold. In this way, the leaked hydrogen will flow out of the stack. According to the above discussion, it can be concluded that there may be a leak between the gasket and the membrane at the anode outlet manifold in the Cells 64 and 67. A schematic of such a probable leak type is shown in Fig. 7.

By further inspection of Fig. 6, it is clear that there are low crossover currents in Cells 20 and 31 in both the direct and the reversed tests. The magnitude of the currents in these cells are much lower than those in Cells 64 and 67 which can be an indication of lower hydrogen crossover leakage in these cells. Since crossover current has been recorded in both the direct and the reversed tests, the source of leakage may be due to some inherent holes in the membrane which may be resulted from the manufacturing processes. The importance of the leak issue in Cells 20 and 31 can be more investigated by analyzing the results of the OCV decay test.

OCV decay test

The OCV decay test was also carried out on this stack in order to build confidence in the crossover current test results. Furthermore, finding the exact location and source of the leakage in the defected cells is also favored.

At the first step, hydrogen and air were delivered to the anode and the cathode sides, respectively. The record of cell voltages before and after pressurizing the hydrogen side is displayed in Fig. 8. For the sake of clarity, the voltage–time diagrams of most of normal cells are not displayed. As seen from this figure, the voltages of Cells 64 and 67 fall rapidly by

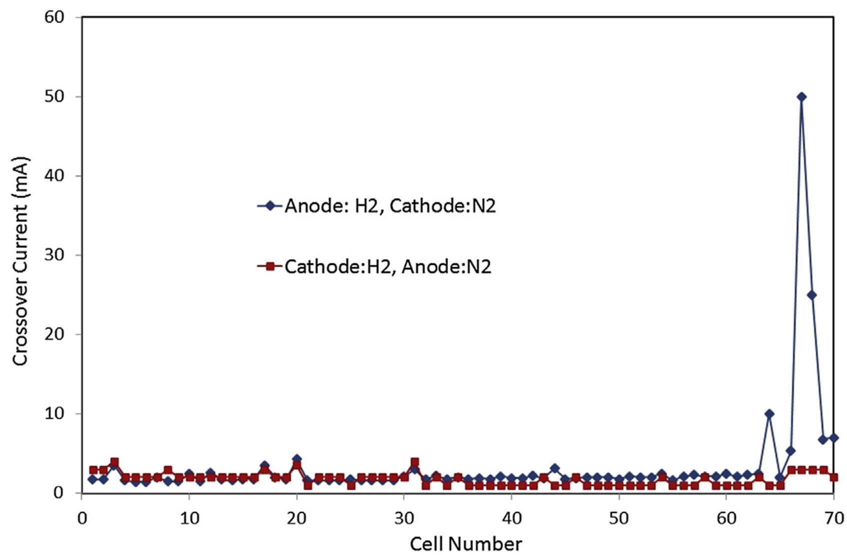

Fig. 6 – Comparison between crossover currents of individual cells in the direct and reverse crossover current tests.

pressurizing the hydrogen side, and after 2.7 min, when the pressure difference is removed, the voltages of these cells increase again and return to a little higher values than the initial ones. The quick decrease of the potentials in the defected cells can be explained by the rapid oxygen consumption in the cathode electrodes, which leads to fast decrease of the O2 partial pressure available at the reaction interfaces. Like as the crossover current test, this test does not say anything about the type of leaks in Cells 64 and 67.

As Fig. 8 shows, in addition to Cells 64 and 67, the OCVs of Cells 62, 66 and 69 have dropped slightly by pressurizing the hydrogen side. Now the main question is: are these voltage drops in Cells 62, 66 and 69 caused by any leak in them? Or they are due to natural diffusion of hydrogen through the membrane or they are due to transferring of leaked hydrogen from the adjacent defected cells to the air sides of these cells? This question cannot be easily answered by the OCV decay test, but it may be answered by referring to the results of crossover current tests. The diagrams in Fig. 6 show that there are not considerable crossover currents in Cells 62, 66 and 69 which is an indication of no evident leak in these cells. Therefore, it can be concluded that the voltage drops in Cells 62, 66 and 69 are not due to direct leak in these cells. They may be due to transfer of leaked hydrogen from the adjacent defected cells (Cells 64 and 67) to the air side of these cells through the inlet or the outlet air manifolds.

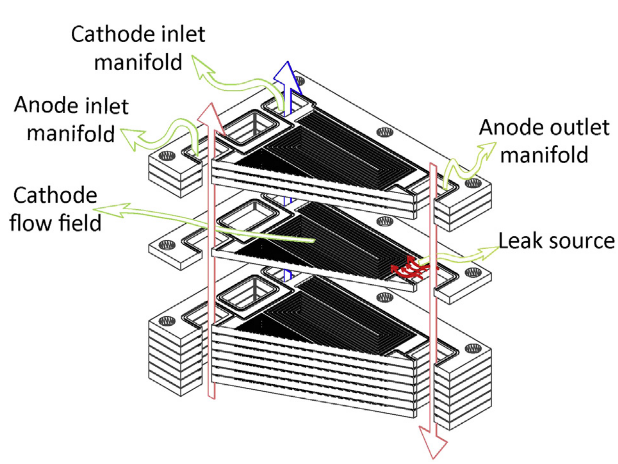

Fig. 7 – A schematic of leak type in the stack; reactant gases flow from anode inlet manifold into cathode flow field through a breach in the seal.

While, as stated previously in section Crossover current test for locating anode/cathode leak source, the results of the crossover current tests (Fig. 6) show that there are low crossover currents in Cells 20 and 31 which is an indication of low leakages in these cells, the results of the OCV decay test (Fig. 8) show that the amount of leakage in these cells is not high enough to cause voltage drop by pressurizing the hydrogen side. It means that the crossover currents in these cells recorded during the test are not due to leakage in these cells.

We also carried out further OCV tests to find the leak sources in Cells 64 and 67. Again, like as for the crossover current test, another voltage decay test was carried out by reversing the hydrogen and the air sides to find the leak types in Cells 64 and 67. The anode and the cathode sides were purged by nitrogen for 10 min, after finishing the first OCV decay test and before starting the other one. In this test, air was delivered to the stack via the anode inlet port.

Fig. 9 shows the record of the cell voltages before and after pressurizing the hydrogen side. For the sake of clarity, the voltage–time diagrams of most of normal cells are not displayed. As seen from this figure, the cell voltages are not much influenced by the pressure difference between the hydrogen and air sides. It means that if there is any leak from hydrogen side to the air side, it does not leak into anode flow field of cells (air side), because, if this the case, we should see OCV drop in the cells with leak. It seems that if there is any leak from the hydrogen side to the air side, it exits the stack via the anode (air side) outlet manifold without entering to air side of any cell in the stack.

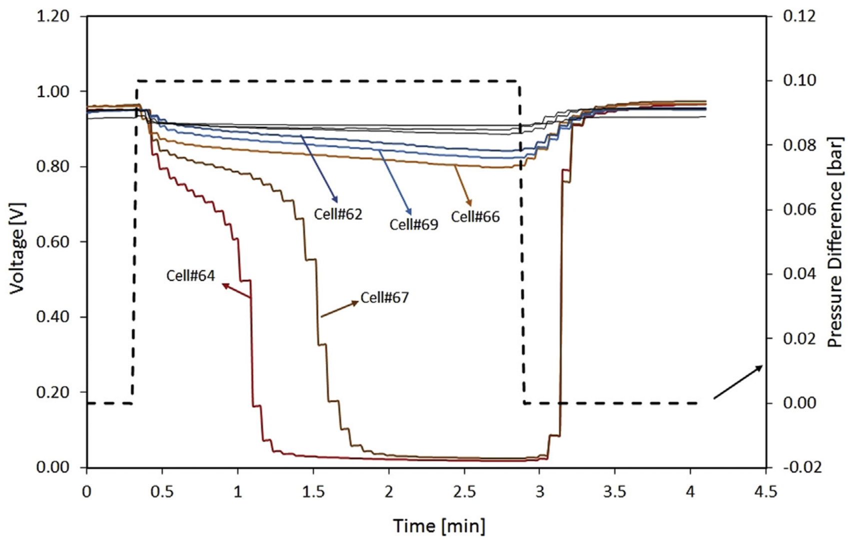

Fig. 8 – Evolution of the cell open circuit voltages during the pressurizing cycle of the hydrogen side.

In order to confirm this hypothesis, it was decided to reverse the air inlet and outlet ports. In this way, air entered and exited the stack via the anode outlet and inlet manifolds, respectively. Fig. 10 shows the record of the cell voltages after pressurizing the hydrogen side. As this figure shows, the OCVs of Cells 63, 64 … 70 start to fall with different rates according to the cell positions in the stack by pressurizing the hydrogen side. Therefore, only OCVs of cell 63 and subsequent cells are mainly affected by the leak. It seems that there may be some leaks from cathode flow field (hydrogen side) to the anode outlet manifold (air inlet manifold) which causes flowing of hydrogen to the air sides of cell 63 and the subsequent cells. According to the above discussion, the existence of a leak from the cathode flow fields of cell 63 and/or subsequent cells to the anode outlet manifold, as shown schematically in Fig. 7, is most probable.

Thermography test

The infrared picture of the stack under test is shown in Fig. 11. As this figure shows, there is a local temperature increase at the upper left corner near to the end of the stack. This higher temperature region is located close to the anode outlet manifold. Hence, it is clear that there is a leak from the anode manifold to the cathode flow field in this region which causes combustion, heat generation and temperature increase. This picture clearly shows that the leak is occurring around the one end of the stack. However, it is almost hard to exactly determine the location of the defected cells.

As seen from this picture, the main advantage of the IR thermography method is that the leak diagnosis can be carried out easily and rapidly only by the visualization, without the need for the hard efforts of interpreting the test results as those are done in the cases of the crossover current or the OCV

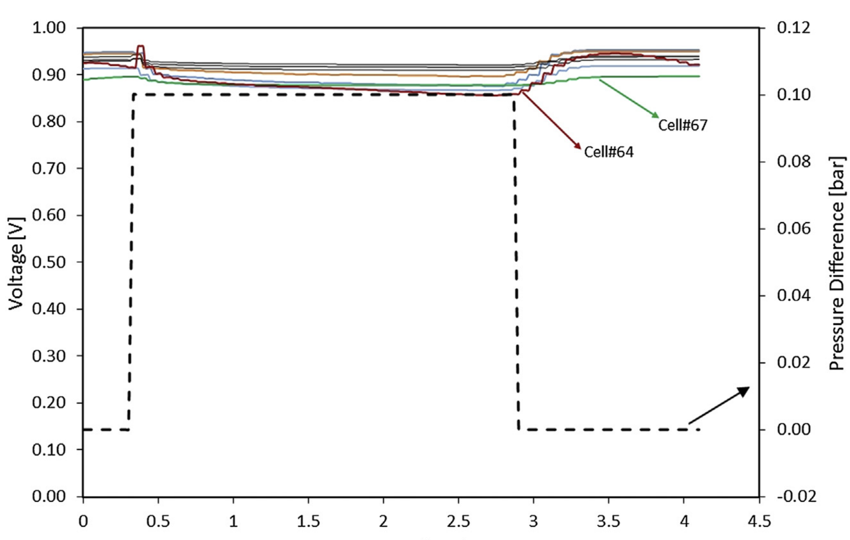

Fig. 9 – Evolution of the cell open circuit voltages during the pressurizing cycle of the hydrogen side in the reversed test.

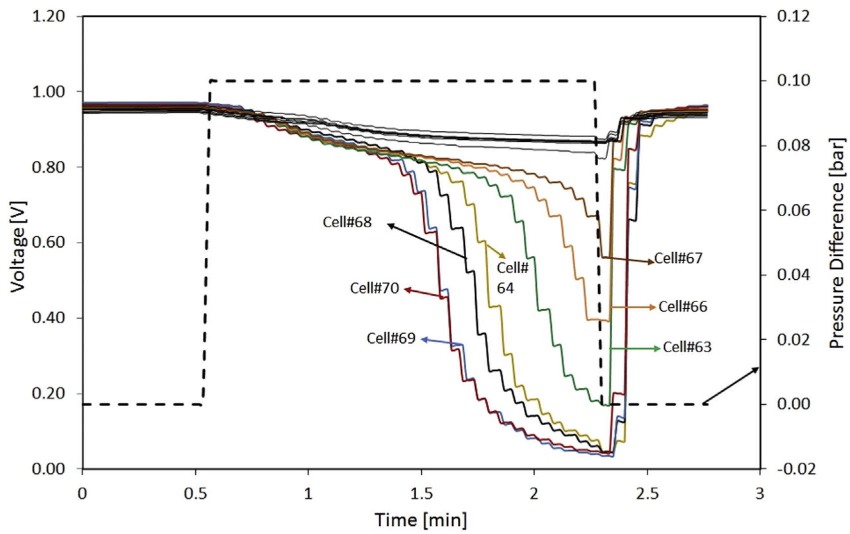

Fig. 10 – Evolution of the cell open circuit voltages during the pressurizing cycle of the hydrogen side in the reversed test in the case where air enters the stack via anode outlet port.

decay tests. The main limitation of the method is the restricted ability to find the exact location of the leak in the stack. Because, the generated heat in the defected cell transfers to the adjacent cells by the conduction through the bipolar plates or by the flowing air which leads to the temperature increase in these adjacent cells. The heat transfer leads to the formation of a wide area with increased temperature around the defected cell.

Finally, disassembling of the stack showed that there were some gasket defects in Cells 64 and 67 which caused anode/cathode leakage.

Second stack

Pressure decay tests indicated that there was a crossover leakage between the anode and the cathode compartments, and also there was a leakage between the cooling and the cathode compartments, too. Some leak diagnosis tests were performed on this stack to find the leak locations. The results of the tests are discussed in the following sections.

Crossover current test for locating anode/cathode leak source

This test was carried out under two different conditions: one in which hydrogen and nitrogen were delivered to the anode and the cathode sides, respectively, and the cooling compartment was free; one in which hydrogen was supplied to the anode and the cooling compartments, and nitrogen was supplied to the cathode side. In the second test, the anode and the cooling compartments were pressurized simultaneously. The tests were performed under different nitrogen flow rates ranging from 10 to 180 SLPM, as for the first stack. The test results showed that, unlike at the lower flow rates (10-80

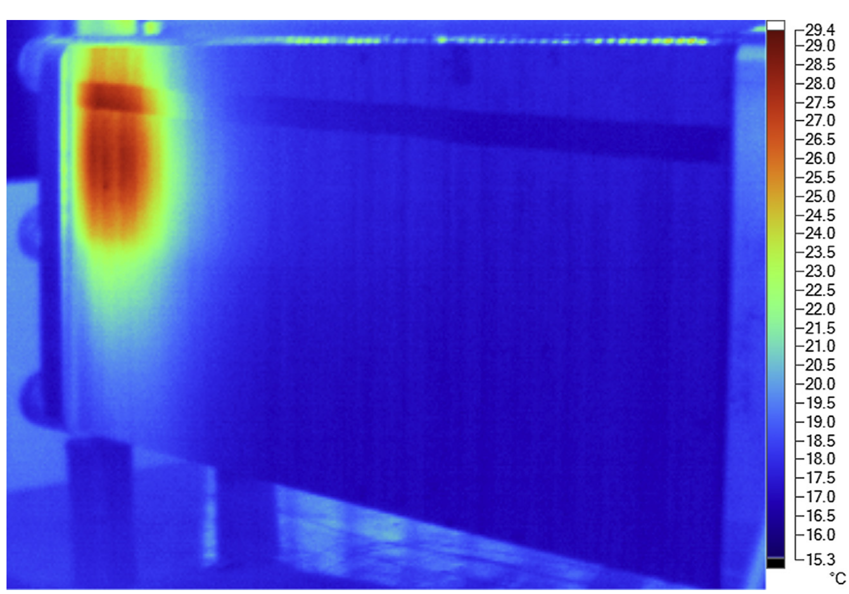

Fig. 11 – Infrared thermal image of the first stack under thermography test.

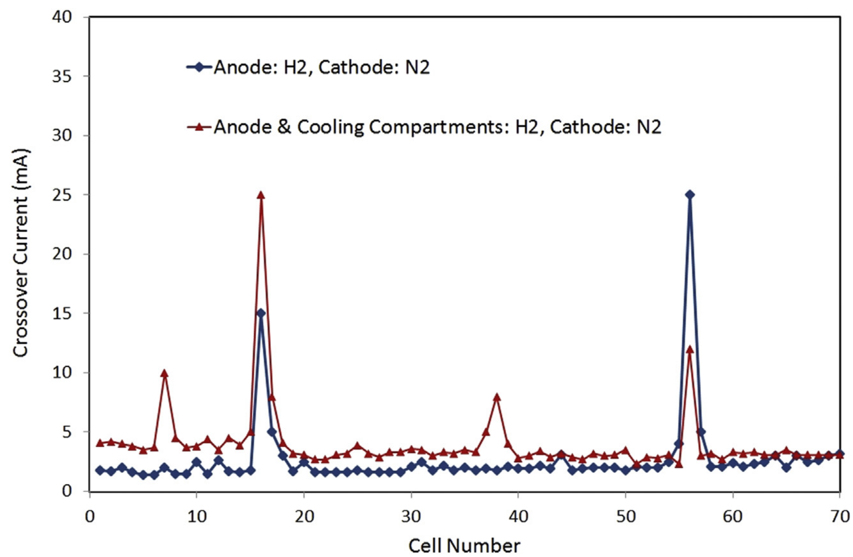

Fig. 12 – Comparison between crossover currents of individual cells in two cases:1) anode and cathode are fed with hydrogen and nitrogen, respectively, and cooling compartment is free, 2) anode and cooling compartments are fed with hydrogen and nitrogen is delivered to cathode.

SLPM), an increase of 30 SLPM nitrogen flow rate from 150 SLPM to 180 SLPM did not have any considerable effect on the results. In other words, the flow rate of 180 SLPM was an optimized value which gave the best sensitivity.

Fig. 12 shows the crossover currents of cells in the stack obtained in the two above-mentioned tests at the nitrogen flow rate of 180 SLPM. The test results in the case of cooling compartment being free of hydrogen indicate that there are leaks in Cells 16 and 56. But as seen from this figure, when the cooling compartment is fed by the hydrogen and pressurized along with the anode side, two more cells (Cells 7 and 38) show leak. Hence, it can be concluded that there are anode/cathode leakage in Cells 16 and 56; and cooling/cathode leakage in Cells 7 and 38.

Some infrared pictures were taken during the crossover current test in the case where hydrogen was delivered simultaneously to the anode and the cooling compartments. Fig. 13 shows the infrared picture of the stack under test. The leak locations can be visualized easily as for the first stack. As this picture shows, there are about four local temperature increases at different locations in the stack. Further investigation reveals that these temperature increases are located around Cells 7, 16, 38 and 56. In addition, intensity of temperature increase is higher at Cells 16 and 56 where there are anode/cathode leakages. This can be an indication of higher leak flow in these cells than the cooling/cathode leak flow exists in Cells 7 and 38.

OCV decay test

The OCV decay test was carried out on the stack in two different conditions: one in which hydrogen and air were supplied to the anode and the cathode respectively and the cooling compartment was free, and one in which hydrogen was supplied to the anode and the cooling compartments and air was delivered to the cathode side. Fig. 14 compares the cell voltages recorded during these two tests before and after pressurizing the hydrogen side. For the sake of clarity, the voltage–time diagrams of most of intact cells are not displayed. As seen from part (a) of this figure, in the case where hydrogen is only supplied to the anode side, the OCVs of Cell 16 and 56 fall rapidly, but in the case where hydrogen is delivered to the cooling side along with the anode side (Fig. 14b), the number of cells whose OCV drops quickly, increases up to four cells. Like the other tests have shown so far, this test confirms the idea that the leak type in Cells 7 and 38 is of cooling/cathode type.

OCV growth test

This test was done according to the procedure and conditions described in section Leak testing from cooling compartment to other compartments (OCV growth test). Fig. 15 shows the evolution of cell open-circuit voltages during pressurizing cycle in the cooling compartment. As seen from this figure, the OCVs of Cells 38 and 7 start to increase, respectively, as the cooling compartment is pressurized. This is an indication of the cooling/cathode leak type which causes leakage of hydrogen from the cooling compartment to the cathode compartment. However, after a while, the OCVs of all cells in the stack start to grow, because amount of leakage is high enough to cause transfer of hydrogen from cells with leak to intact cells via inlet and outlet manifolds.

As presented above, only one test was needed to localize the cathode/cooling leak type in the stack by the use of OCV growth method. In other words, while the OCV decay and the crossover current test methods need two or more separate tests to find the location of the anode/cooling or the cathode/cooling leaks in the cases where both the reactant gases/cooling and the anode/cathode crossover leak types exist in the stack, the OCV growth method can do this by only one test. Therefore, the main advantage of this test method is isolating the cells with cathode/cooling or anode/cooling leak types from the cells with anode/cathode crossovers by performing

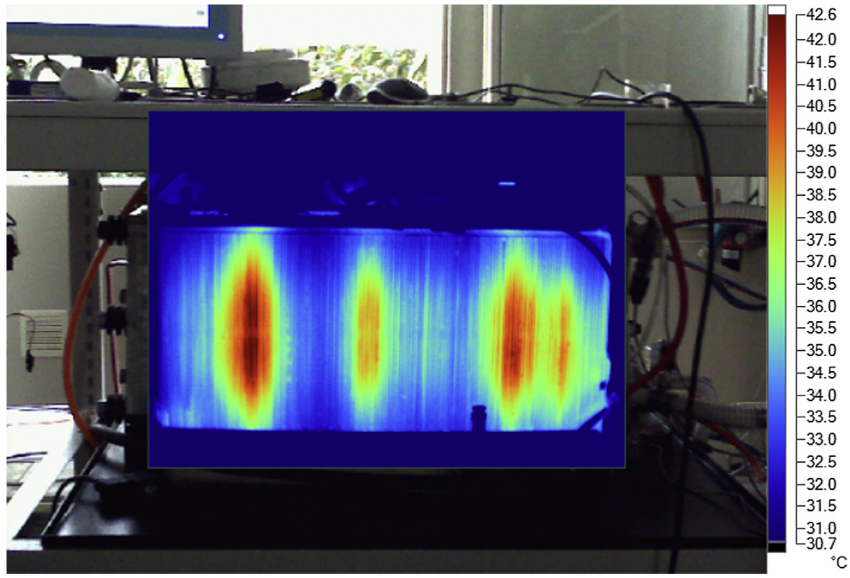

Fig. 13 – Infrared thermal image of the second stack under thermography test.

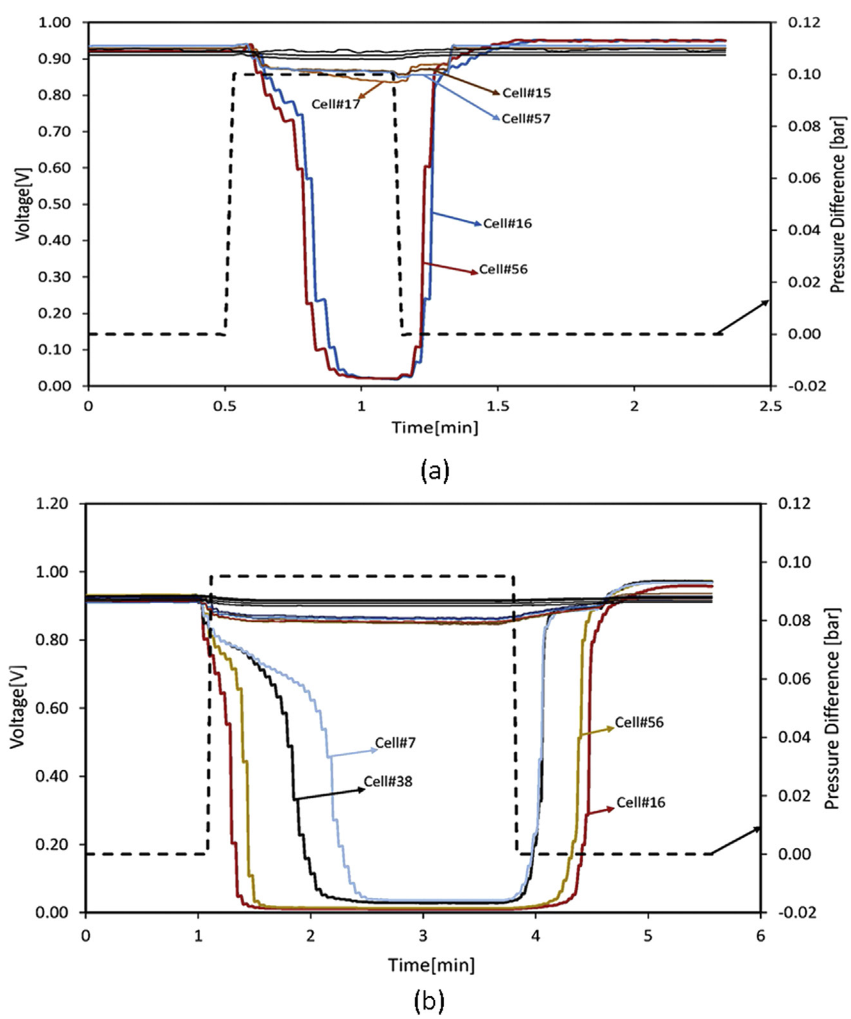

Fig. 14 – Evolution of the cell open circuit voltages during the pressurizing cycle of the hydrogen side in two cases: a) Hydrogen is supplied to anode and cooling compartments and air is delivered to cathode side. b) Hydrogen and air are supplied to anode and cathode, respectively, and cooling compartment is free.

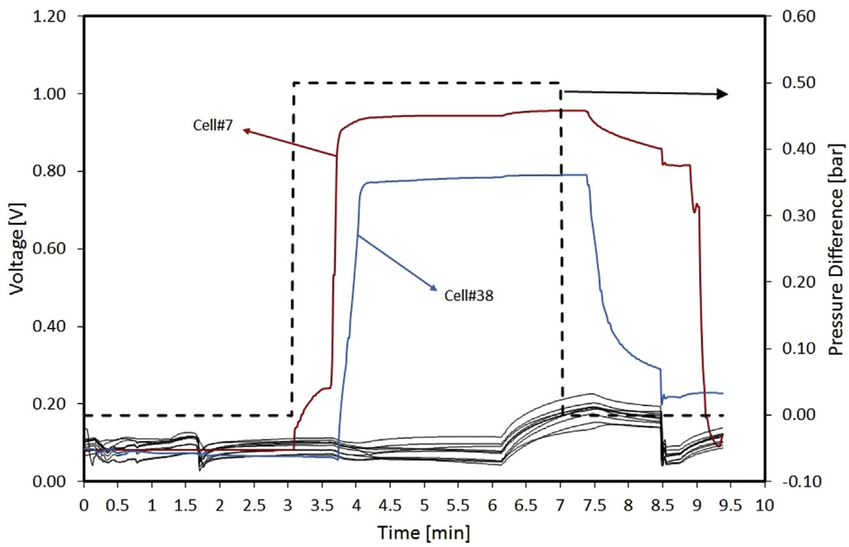

Fig. 15 – Evolution of the cell open circuit voltages during the pressurizing cycle of the hydrogen side in the OCV growth test.

just one test. The main limitation of this technique, as seen from Fig. 15, is restriction on the duration of the test. Because in the cases where the test lasts long, the leaked hydrogen from the defected cells has enough time to be transferred to the intact cells via the manifolds (especially when the leakage rate is high) and therefore the OCV of the intact cells start to raise as a result. By this way, the intact cells may be grouped into defected cells by wrong. On the other hand, in the cases where the test duration is short, there is not enough time to let the hydrogen to leak from the cooling compartment to the anode or cathode compartments (especially in the cells with low leakage rate) and to increase the OCV in the defected cells. Therefore, the number of defected cells with reactant gas/cooling leak type may be underestimated. Therefore, the test duration needs to be optimized.

Opening the stack assembly revealed that there was bipolar breakage during the assembly process in Cells 7 and 38 which caused cooling/cathode leakage. There were also some gasket defects in Cells 16 and 56 which caused anode/cathode leakage.

Conclusion

The present article presented some test data and descriptions related with two PEMFC stacks which had anode–cathode crossover or/and cathode-cooling leak at the beginning of life after the assembly process. Some practical guidelines and explanation of experimental diagnosis procedures were provided. These diagnosis procedures can be used to detect the leak sources and types inside the FC stack without opening the stack assemblies. In this way, the integrity of intact cells in the stack is preserved. Open circuit voltage decay, crossover current and IR thermography tests can be used in determining and localizing the anode/cathode crossover. Since hydrogen and air are not used simultaneously in the stack, the crossover current test is safer than the other procedures. But the test results are strongly dependent on the nitrogen flow rate and, therefore, much effort is needed to optimize nitrogen flow rate to obtain the best sensitivity. Infrared thermal imaging can be used during the open circuit voltage decay test in order to build confidence in the test results.

OCV decay, crossover current, thermal imaging and OCV growth tests can be deployed to help in localization of the leakage origins in the stacks which have anode/cooling or cathode/cooling compartment leaks. Since the diagnosis test duration with hydrogen supply should be as short as possible, OCV growth test is preferred. Because, this test method can locate the leak source in lower test duration in comparison with the other diagnostic methods.

The results of the IR thermography showed that this technique has a good potential to be used along with the other methods in the leak diagnosis of the PEMFC stacks. Finally, since there may be some uncertainty in the location and type of leak in the stack found by a test, it is suggested to perform two or more different leak diagnosis tests on the stack and compare the results in order to build confidence in the test results.

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