Fuel Cell End Plates: A review

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The end plates of fuel cell assemblies are used to fasten the inner stacks, reduce the contact pressure, and provide a seal between Membrane–Electrode Assemblies (MEAs). They therefore require sufficient mechanical strength to withstand the tightening pressure, light weight to obtain high energy densities, and stable chemical/electrochemical properties, as well as provide electrical insulation. The design criteria for end plates can be divided into three parts: the material, connecting method, and shape. In the past, end plates were made from metals such as aluminum, titanium, and stainless steel alloys, but due to corrosion problems, thermal losses, and their excessive weight, alternative materials such as plastics have been considered. Composite materials consisting of combinations of two or more materials have also been proposed for end plates to enhance their mechanical strength. Tie-rods have been traditionally used to connect end plates, but since the number of connecting parts has increased, resulting in assembly difficulties, new types of connectors have been contemplated. Ideas such as adding reinforcement or flat plates, or using bands or boxes to replace tie-rods have been proposed. Typical end plates are rectangular or cylindrical solid plates. To minimize the weight and provide a uniform pressure distribution, new concepts such as ribbed-, bomb-, or bow-shaped plates have been considered. Even though end plates were not an issue in fuel cell system designs in the past, they now provide a great challenge for designers. Changes in the materials, connecting methods, and shapes of an end plate allow us to achieve lighter, stronger end plates, resulting in more efficient fuel cell systems.

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1. Introduction

A proton exchange membrane fuel cell (PEMFC) uses a polymer as an electrode, and is also known as a solid polymer electrolyte fuel cell (SPEFC), a solid polymer fuel cell (SPFC), or a polymer electrolyte fuel cell (PEFC). A PEMFC has a low operating temperature and high efficiency, electric current density, and output density, as well as a short start-up time, and it provides a fast response to load changes.

A PEMFC consists of a cathode and an anode, with a polymer electrolyte membrane placed at the middle. The inner stacks are composed of separators and bipolar plates. The composition and performance of the Membrane–Electrode Assembly, which is made by hot pressing the electrode on the polymer membrane, is the core technology of fuel cells.

The critical factor influencing the performance of the MEA is the clamping pressure. If the clamping pressure is too small, the interfacial contact resistance between the MEA and the bipolar plate will increase, decreasing the efficiency of the fuel cell system. The efficiency also decreases if the clamping pressure is too large.[1]

End or pressure plates, located on the outer side of the stacks to provide the proper pressure, are compressed using appropriate connecting techniques such as tie-rods. A rough sketch of the structure of a fuel cell with end plates is given in Fig. 1.

Because end plates should not deform under operating temperatures, pressures, and moisture conditions, they must have a certain degree of mechanical strength and stiffness. They have a fuel inlet and outlet, a coolant circulation hole, and a connection hole. To prevent the MEA from dehydrating, the intake gas is moisturized. The outlet gas can be mixed with water, which forms from the reaction of hydrogen and oxygen. Thus, the end plate requires a sufficient electrochemical stability to endure the above contaminations.

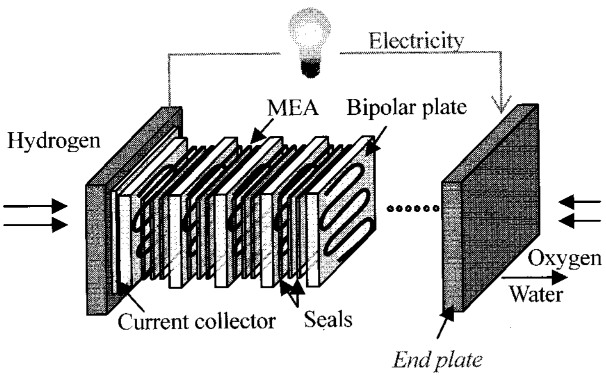


Fig. 1 Schematic view of PEM fuel cell

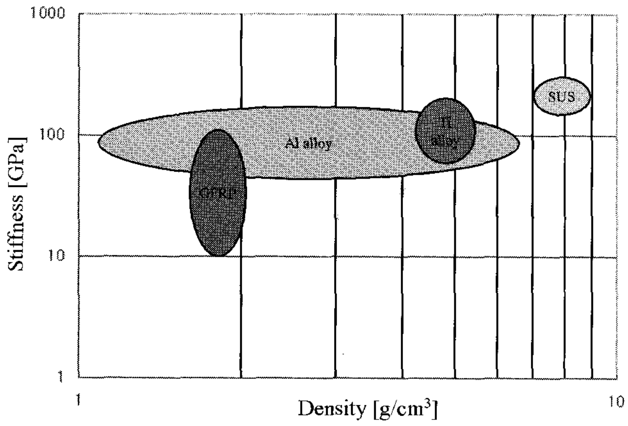


Fig. 2 Comparison of stiffness vs. density of end plate materials

High-power PEMFC stacks consist of hundreds of single cells emitting high voltages. To ensure the safety of users, the end plates must provide electrical insulation. A low density is also desirable to obtain a high voltage to weight ratio.

To develop end plates that satisfy the aforementioned features, we considered the following three design criteria:

1. classification by materials
2. classification by connecting methods
3. classification by shape

2. Classification by Material

The most common material used for end plates in the past was metal. Studies of other materials that also yield the desired performance are in progress. The desired features of an ideal material for an end plate are

- Low density
- High mechanical strength and stiffness
- Excellent electrochemical stability
- Electrical insulation.

2.1 Metal

Most metal end plates are made from aluminum, titanium, or stainless steel alloys.[2]

2.1.1 Aluminum Alloy

Aluminum alloy has a lower density and higher strength than other metals (Fig. 2). Since the material is easy to manufacture, aluminum alloy is widely used for end plates.

2.1.2 Titanium Alloy

Titanium alloy also has a low density and high strength, and is strongly resistant to corrosion, but due to its high cost, titanium alloy is not as widely used.

2.1.3 Stainless Steel Alloy

The good mechanical properties and low price of stainless steel alloys have made them the mostly widely used material for end plates. However, SS316L, which is used in PEMFCs, induces degradation of Nafion, a fluorine type of membrane.[3]

2.1.4 Issues in Metallic End Plates

Metals have high mechanical stiffness and are resistant to heat. However, when used for long periods of time, metal end plates exposed to air, water, or vapor corrode, and metal ions diffuse into the electrolyte. This phenomenon increases the electrical resistance, which causes output voltage and the ionic conductivity to drop.

Surface coatings that provide sufficient corrosion resistance have been proposed to overcome this problem. Formerly, gold was coated on stainless steel or aluminum alloy end plates to increase the contact resistance, but this method has certain drawbacks.[4,5] First, gold is very expensive. Second, the adhesion between gold and the end plate material is not sufficient to hold the two materials together, so a second coating of nickel has to be added between the gold and end plate material. Recently, instead of gold, an aluminum oxide film or porous aluminum oxide layer has been applied to the surface of aluminum alloy end plates[6], and epoxy coatings have also been studied to enhance corrosion resistance.[7,8,9]

The use of a sealant coating with electrical insulating properties on stainless steel end plates has been studied. The coating is applied using a dispenser printing method, after which a current collector can be attached and pressurized to combine the above materials.[10]

Coating methods have complex manufacturing processes and increase the material cost. To operate a fuel cell system, the fuel cell is first heated to the operating temperature. Metal end plates take more time to reach the operating temperature due to their high thermal capacity, and the high thermal conductivity of metal increases the heat loss, necessitating additional heat insulators.[11]

2.2 Nonmetals

Nonmetal end plates have been recently studied in an attempt to overcome the weak points of metal materials. Nonmetals are lighter and cheaper than metals, and their thermal conductivities and capacities are smaller than metal, reducing the heat loss. Their corrosion resistance is also better than that of metals.[12]

Phenolic plastics have no electrical conductivity and provide sufficient corrosion and hydrogen resistance, and plastic end plates can be manufactured using injection molding techniques.[13] Polyethylene, polypropylene, polyamide plastic, polycarbonate, polyester, polybutylenes terephthlate, polyether, phenolic resin, and polystyrene including acrylonotrile–butadiene–styrene (ABS) have been studied.[14]

Pure nonmetal end plates have not been commercialized, and while they overcome the weak points of metals, their reliability is reduced due to their lower mechanical strength.

2.2.1 Partial Nonmetals

Robin (1998) manufactured end plates with only portions made from plastic. The plate connections were located on the metal portions.[15]

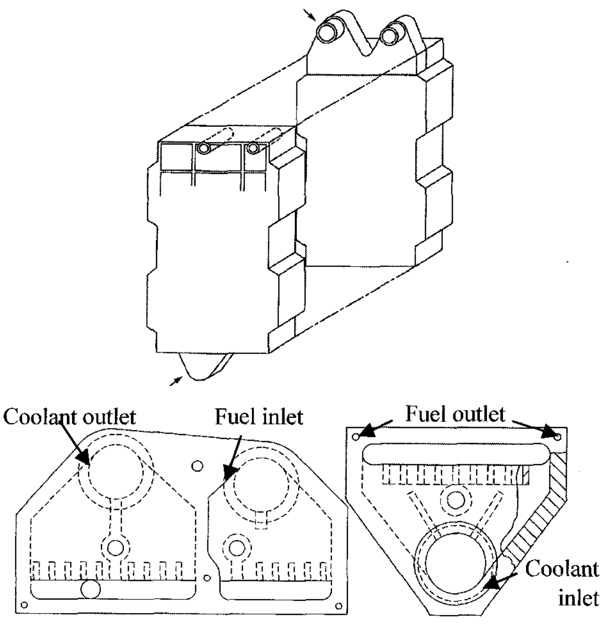


Fig. 3 Positive/negative end plate assembly with header (top), detailed view of the header in positive (bottom left), negative end plate assembly (bottom right) (modified from Ref. 15)

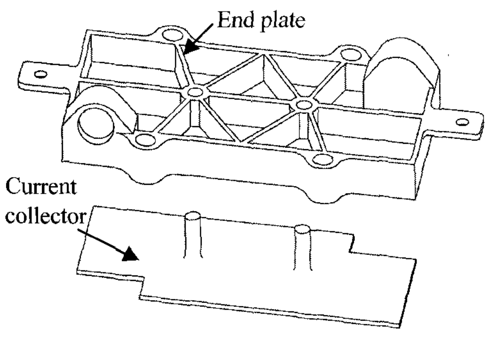


Fig. 4 Nonmetal end plate and current collector (modified from Ref. 5)

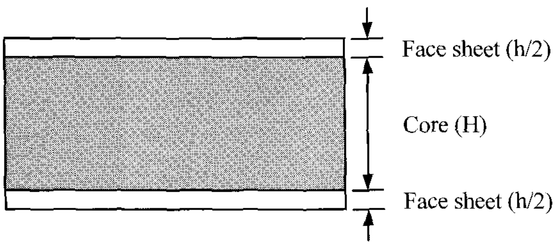


Fig. 5 Schematic sandwich plate structure

The fuel and coolant inlet/outlet headers were manufactured separately as shown in Fig. 3. They were designed to be connected using metal end plates. Plastic, such as glass fiber, was used to manufacture the headers.

By using a partially nonmetal material, corrosion of the end plate can be prevented and the total weight of the end plate can be reduced.

2.2.2 Composites

Since single-component nonmetals do not have the mechanical strength of metals, composite materials are becoming more common. Composites are a combination of two or more base materials that are physically different, and are used to obtain the base material properties while providing a synergy effect of the materials.[16]

Morrow (2003) reported that both end plates and current collectors can be manufactured from nonmetal materials.[5] He used fiber-reinforced composite materials for end plates and graphite materials for current collectors. The resulting end plates and current collectors were very light and had small thermal capacities. (Fig. 4)

Composite end plates with glass, carbon, Kevlar, or ceramic powder on plastic resin have been studied. [14,17,18] When end plates were fabricated from glass fabric and thermoplastic resin, their creep resistance and dimensional stability improved. Thermosetting resins with inorganic fillers have also been used to fabricate end plates.[12] Epoxy, silicone, or polyester resins can be used as thermosetting resins, and crystal silica, alumina, boron nitride, glass fibers, carbon fibers, and ceramic fibers can be used as inorganic fillers. After fabrication, a waterproof coating can be applied to increase the corrosion resistance and smooth the flow of water, carbon dioxide, and oxygen.

2.2.3 Sandwich Plate Structure

To obtain a higher mechanical strength, Ahn (2004) proposed a new concept for an end plate consisting of a sandwich plate structure (SPS) with two different composite layers. As shown in Fig. 5, polyurethane foam was used for the core while glass fiber reinforcements with vinyl ester resins were used for the face sheets.[19]

Crushing and compressive creep tests were performed on the fabricated structures. The test results indicated that the SPS structure had sufficient strength and life to be used as an alternate for stainless steel. The total weight of the end plate could be reduced without sacrificing its structural reliability. Ahn (2004) also proposed a double sandwich structure with an additional metal part to increase the strength further.

Thermal analysis results indicated that the end plate thermal transfer properties were very small, suggesting that an SPS end plate is a very effective thermal insulator.

3. Classification by Connecting Method

The mechanical strength of an end plate material is used to withstand the connecting pressure. The connecting pressure must be equally distributed over the entire end plate since an unequal pressure distribution causes gas/coolant leakage and heat loss. The discrepancy of the thermal stress due to heat loss causes nonuniform deformation.[20] Therefore, the methods used to connect the end plates are critical. Originally, end plate materials were only made from metal, and the choice of the connecting method was not very important. However, since new nonmetal and composite materials are now being used for end plates, the connecting method has become a very important factor in end plate designs, and new connecting methods are being investigated.

3.1 Tie-rod and Bolt

3.1.1 Description

A general method used to connect end plates consists of tightening the outside of an end plate with several bolts. This connecting method, described in Fig. 6, is known as the "tie-rod and bolt" method.[21] Several holes are drilled in the end plate, and tie-rods are passed through these holes. Bolts and nuts are fastened to the ends of the rods, providing the proper pressure to the inner stacks.

Hence, the number and positions of the tie-rods are key factors in the end plate design. Other examples are given in Fig. 7.[6,23,24]

The tie-rod and bolt method requires thick end plates to give a uniform compression stress, decreasing the power density to volume ratio. Many additional parts, such as bolts, nuts, and washers, must be used, increasing the cost and assembly time.

3.1.2 Reinforcement Plate

The reinforcement plate method consists of adding a plate spring-shaped part. By using a reinforcement plate, the displacement that originated from the stress between the current collector and end plate can be minimized so that compressive stress can be uniformly distributed (Fig. 8). Thus, the reinforcement plate acts like a spring, transferring a uniform pressure without any other shock absorbers.

The main advantage of a reinforcement plate is that it offers reliable connecting performance.

Adding a reinforcement plate decreases the thickness of the end plate. By changing its shape, a more effective pressure transfer can be achieved. The connecting part of the reinforcement plate does not include the end plate, decreasing the local stress concentration and achieving a uniform pressure distribution.[20]

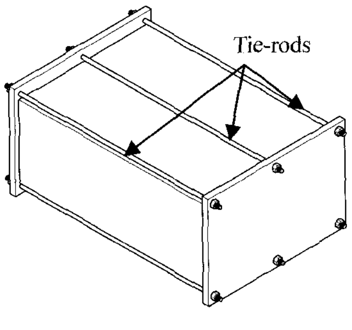


Fig. 6 Tie-rod and bolt method (modified from Ref. 21)

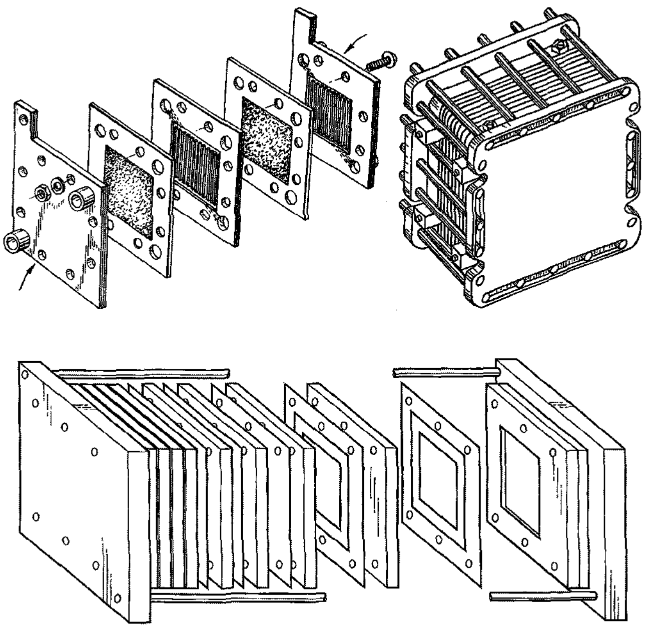


Fig. 7 Other tie-rod and bolt methods, (top left) (modified from Ref. 6), (top right) (modified from Ref. 23), and (bottom) (modified from Ref. 24)

However, the manufacturability of a reinforcement plate is poor, and complexity of the shape can be concern.

3.1.3 Interference Fit

The interference fit method uses the friction force between the stack components and bars to fix the stacks. Because the outer area of each stack is punched, the stacks can be fixed by inserting bars in these holes (Fig. 9) .

The cross-sectional shapes of the holes and bars are not limited to circles and squares, but they can be any shape. This method simplifies the connecting method, making it easy to assemble and disassemble the fuel cell, but since a small discrepancy can eliminate the system seal, very precise machining is required.[25]

3.2 Box Wrapping Method

3.2.1 Box Wrapping with Bolts

This method consists of a containing box and multiple unit cells, a pressing end plate, and box-penetrating nuts and bolts. A bolt is attached to an end plate and presses against multiple unit cells that are to be pressurized. In case of an explosion due to leakage of hydrogen and oxygen gas, the containing box redirects the force of the blast from the inner stacks, protecting them. Although the assembly productivity is good, the manufacturability of the box-shaped container is poor (Fig. 10).[26]

3.2.2 Box Wrapping with Springs

Another way consists of installing springs between the box and the end plate, adding pressure to the inner stacks. This technique can be subdivided into two separate methods: one using springs on only one side of the end plate, and the other using springs on both sides of the end plate (Fig. 11).[27]

3.3 Flat Board

The flat board method uses a small sliding part connected to a flat end plate. It is easy to assemble and gives a uniform connecting pressure, increasing the durability of the inner stacks. By using a material with a low coefficient of thermal expansion, the stack area can be decreased at the same energy density as the other connecting methods. However, only a few materials can be used for the sliding part.[28]

A similar concept uses four flat end plates, as shown in Fig. 12.[29]

3.4 Other Methods

3.4.1 Band

The stress where nuts are connected in the tie-bar method is higher compared to other positions. The nut positions have nothing to do with the stack output voltage, a dead volume that decreases the output density. In addition, an unnecessary bending load can be applied to the space between the bars and stacks, making it difficult to obtain a uniform stress distribution, and the sealing performance decreases due to the space between the bar and stacks. To resolve these problems, flat or band connectors (Fig. 13) have been proposed instead of tie-bar connectors. These decrease the unnecessary bending load and dead volume. By decreasing the dead volume, the fuel cell becomes a denser and more compact system. The method allows one to attach bands without changing the stack shape. However, it is difficult to distribute the inner pressure uniformly.[21]

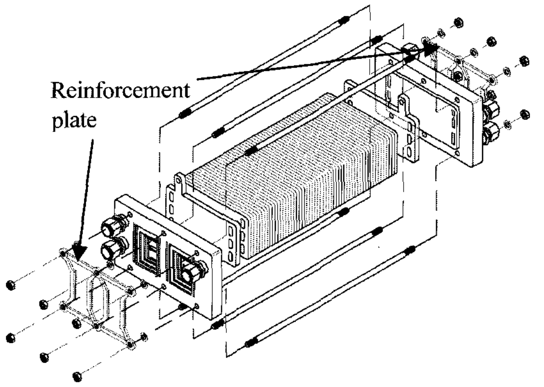


Fig. 8 Reinforcement plate method (modified from Ref. 20)

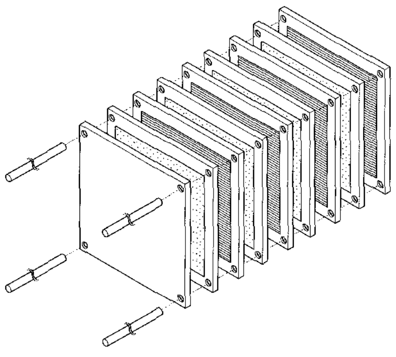


Fig. 9 Interference fit method (modified from Ref. 25)

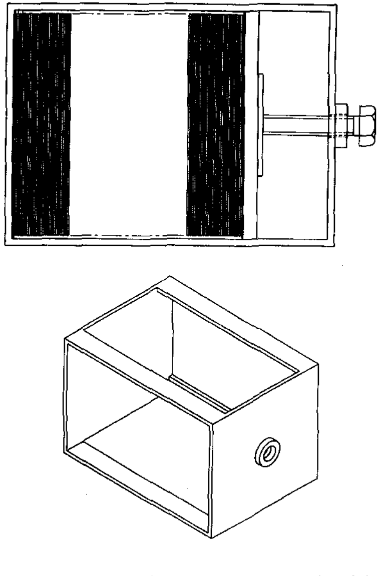


Fig. 10 Box wrapping method. A stack pressurized by the bolt type (top), or box container type (bottom) (modified from Ref. 26)

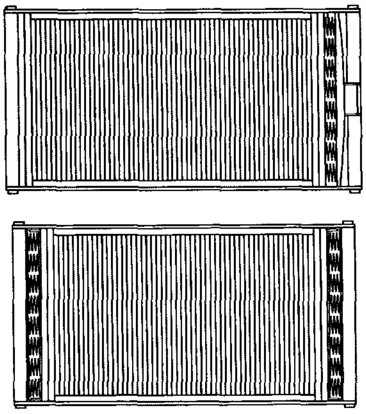


Fig. 11 Box wrapping method using springs. Spring on one side (top), spring on both sides (bottom) (modified from Ref. 27)

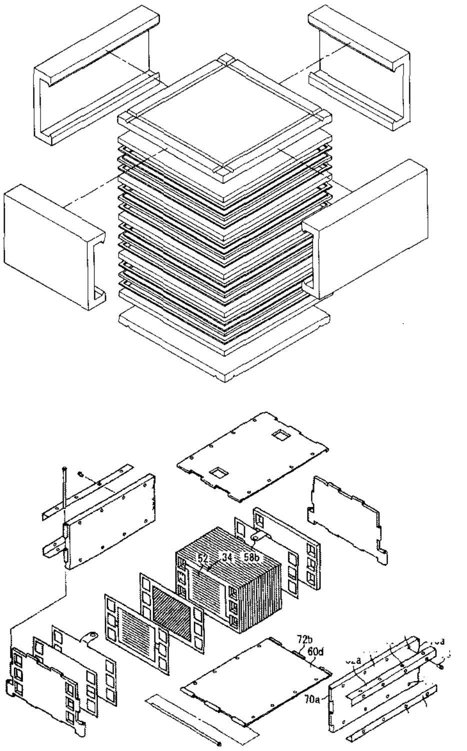


Fig. 12 Flat board method. Sliding type (top) (modified from Ref. 28), and bolting type (bottom) (modified from Ref. 29)

3.4.2 Shape Memory Alloy

This method uses a shape memory alloy (SMA) so that the shape of the end plate shrinks and grows according to the stack temperature (Fig. 14). By using a SMA, deformation of the membrane–electrode assembly can be avoided. The fuel and oxygen transfer is smoother and the performance loss can be reduced.[30]

The most commonly used SMA materials are Ni–Ti, Cu–Zn–Al, and Cu–Ni–Al. Usually, SMA materials are processed in a 2–10% deformation rate at room temperature to achieve a phase changing temperature of austenite at least 50–100°C, and a reverse phase changing temperature of martensite at least –20°C. However, the material costs are very high, and the manufacturing process is very complex.

3.4.3 Gear

This method was designed to provide an easy and convenient membrane–electrode assembly of fuel cell stacks. Multiple nut gears are placed on the end plate and fastened with nuts and bolts. By rotating the gear at the center of the end plate, the nut gears around the center gear rotate together at an equal angle. Equally rotated nut gears fasten nuts and bolts at the same rate, generating a uniform pressure distribution. The local nonuniform pressure distribution due to the tightening procedure can be reduced, preventing bipolar plates or MEA damage. Thus, the manufacturing process can be simplified using the gear method (Fig. 15).[31]

Usually, the center gear is located at the center of end plate, and 3–10 nut gears are connected around the center gear. However, because the center and nut gears only contact at points, insufficient torque is transferred, causing loose tightening. The size, rotational speed, force, and pitches of the gears must be designed considering the number of stacks, performance, and fuel cell dimensions. Even if the gears are perfectly designed, we can obtain a lower pressure than desired due to the backlash of the nut.

3.5 Comparison

The above methods are compared in Table 1.

4. Classification by Shapes

End plates can also be classified by shape. The most common shape is a rectangular solid plate, but many other shapes have been proposed to reduce the weight and increase the strength of the end plate.

4.1 Typical Shapes

Typical types of the end plates are shown in Fig. 16. Rectangular and cylindrical solid plates are the most common types. A ribbed solid plate is a modified version of a rectangular solid plate designed to reduce the weight as much as possible.

Almost all of today's end plate concepts are based on a simple metallic plate. The end plates must be thick for stiffness to obtain a constant pressure distribution inside the stack, but a thick end plate increases the total weight of the fuel cell system and decreases the power to weight ratio. To overcome these shortcomings, new concepts have been suggested.

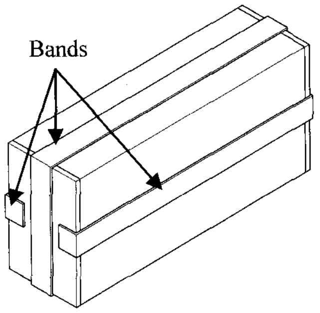


Fig. 13 Band method (modified from Ref. 21)

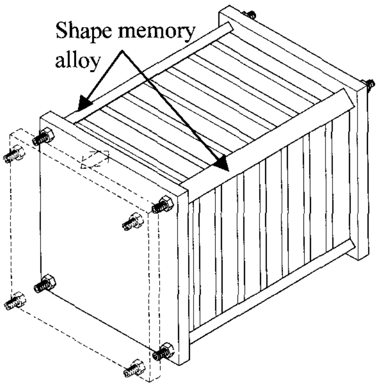


Fig. 14 Shape memory alloy method (modified from Ref. 30)

Table 1 Comparison of connecting methods

		Advantages	Disadvantages
Tie-rod & bolt	Tie-rod & bolt	• Proper pressing stacks possible	• Non-uniform stress distribution • Thick end plate • Hard to assemble/disassemble • Dead volume
	Reinforcement plate	• Reliable connecting performance • Thin end plate • Uniform stress distribution	• Poor manufacturability • Complex shape
	Interference fit	• Easy assemble/disassemble	• Precision machining required
Box wrapping	Box wrapping with bolt	• Safer design • Easy to assemble	• Poor manufacturability
	Box wrapping with spring		
Flat board	Flat board	• Easy to assemble • High energy density	• Material limits
Other methods	Band	• Reducing bending load • No dead volume • Compact design possible • Easy to assemble	• Non-uniform stress distribution
	Shape memory alloy	• Reducing performance loss	• Poor manufacturability • Expensive
	Gear	• Easy to assemble • Uniform stress distribution	• Hard to design • Backlash

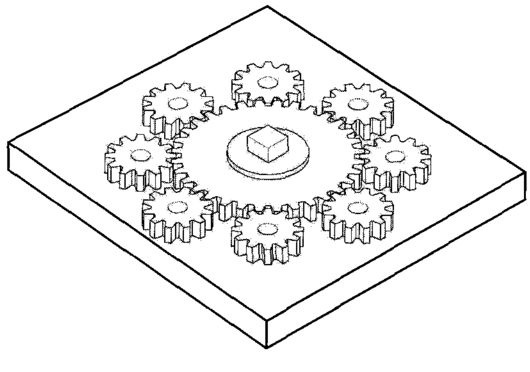
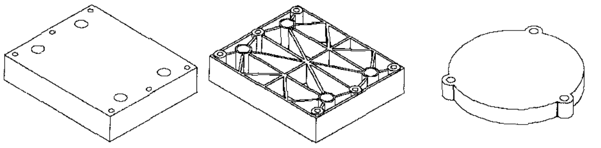


Fig. 15 Gear method (modified from Ref. 31)



a) Rectangular solid plate b) Ribbed solid plate c) Cylindrical solid plate

Fig. 16 Typical types of end plates (modified from Ref. 33)

4.2 Bomb Shape

A very stiff end plate is required to obtain a uniform pressure distribution. Upper figure in Fig. 17 shows a stiff solid end plate with a 0.1 mm deformation on the bottom side. Due to the forces of the external tie bolts, bending of the plate occurs. The deformation varies with the plate thickness.

If the thickness of the end plate decreases, we can reduce the weight of the fuel cell system significantly, but the deformation of the bottom side increases and a uniform pressure distribution cannot be obtained.

To resolve this problem, the end plate can be shaped in a way to compensate for the deformation. In an unstressed situation, the end plate only contacts the middle of the inner side plate. A gap with increasing width toward the tie bolts produces a uniform pressure distribution.

Another concept is to make a flat end plate and a curved inner plate (Fig. 18). A uniform stress distribution can be obtained after tie bolts are applied. This concept is known as bomb shaping.

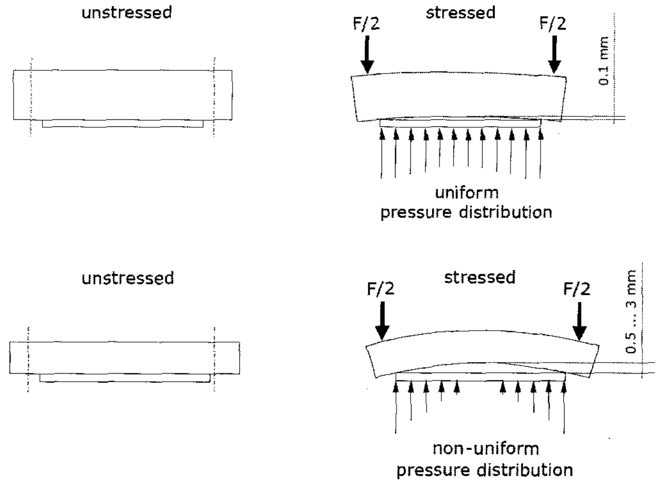


Fig. 17 Nearly uniform pressure distribution using a thin end plate (top), and non-uniform pressure distribution using a thin end plate (bottom) (modified from Ref. 33)

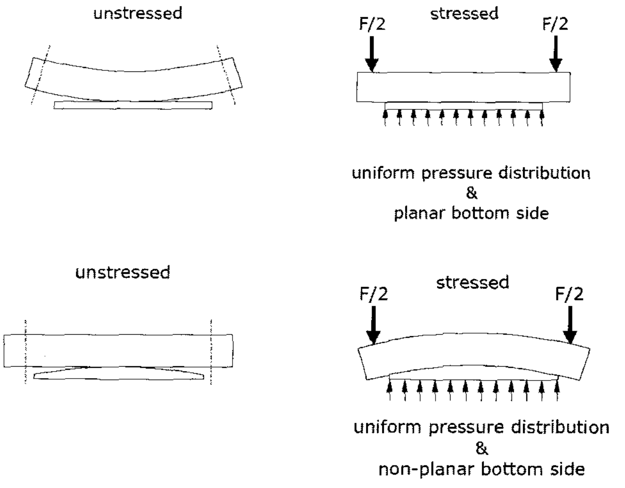


Fig. 18 Bomb shaped end plate with uniform pressure distribution (top), and bomb shaped isolation with uniform pressure distribution (bottom) (modified from Ref. 33)

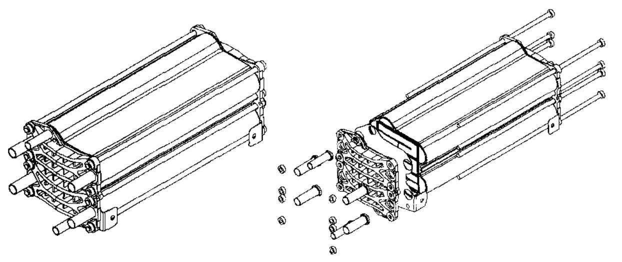


Fig. 19 Stack of the Hy.Power-project (bomb shaped end plate) PowerPac fuel cell stack (modified from Ref. 33)

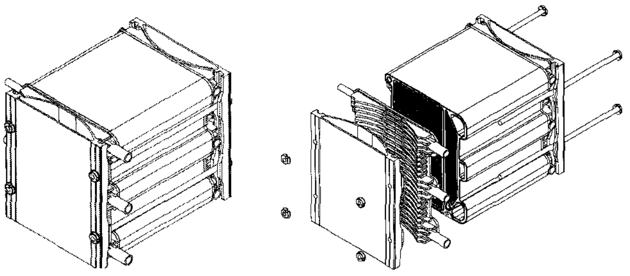


Fig. 20 Stack of the PowerPac with D-Bow end plates (modified from Ref. 33)

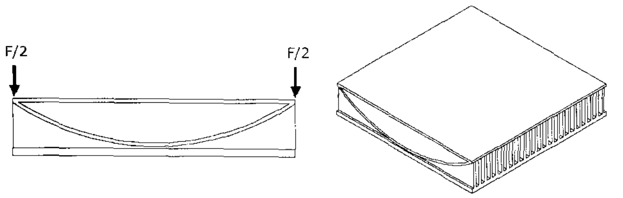


Fig. 21 End plates based on D-bow concept (modified from Ref. 33)

The bomb shaping technique is key to the lightweight construction of fuel cell end plates with significant stack pressures. PSI and ETHZ developed the Hy.Power-Stack, shown in Fig. 19 by applying bomb-shaped end plates. This end plate was designed as a ribbed aluminum part with a bomb-shaped bottom side, and the structure was optimized using a genetic algorithm Finite Element Analysis code.

4.3 D-Bow Shaped

Another type of bomb-shaped end plate is a PowerPac shaped like the letter D. PowerPac is a mobile power generator with an output of 1 kW developed by ETHZ, PSI, Tribecraft AG, and other industrial partners.

The inner plate contains the fuel and cooling supply lines, and permits lightweight construction. This is the D-bow concept. The "D" designates the shape of the end plate while the "bow" indicates the curvature of the end plate and the inner plate shape.

The main idea of this concept revolves around the curvature of the bottom side, similar to a water dam. The stack pressure acts in the normal direction to the bottom side of the pressure plate, while a right curvature of the bottom side will produce pure compression (Figs. 20 and 21).

Because of the D-bow concept, the end plate can be separated into tension compression loading parts, minimizing the expenditure of materials.[32]

5. Conclusions and Future Works

An end plate is a device used to distribute a uniform pressure to the inner stacks of a fuel cell system. It requires a stable operating environment and sufficient strength to withstand the generated pressure during operation, and it must be light and provide electrical insulation.

Aluminum, titanium, and stainless steel alloys are commonly used for end plates. Alternative materials, such as plastics, have been considered due to their low corrosion resistance, thermal loss, and weight, but the lower strength and stiffness of nonmetal materials makes it difficult to produce a pure nonmetal end plate. For these reasons, composite materials that combine two or more materials to obtain a synergy effect have been recently studied.

The connecting method is a very important design criterion for obtaining a uniform distributed pressure. The tie-rod method is often used, but the different materials and increasing number of connecting parts found today have resulted in difficulties in assembly, causing researchers to consider new types of connections. Ideas about supplementing existing connecting methods by adding reinforcement plates or flat plates beside the stacks, and using gears or SMAs have been proposed. The entire connecting method can also be changed to use bands or boxes without tie-rods.

Typical end plate shapes are rectangular or cylindrical solid plates. To minimize the weight and provide a uniform pressure distribution, new concepts have been suggested, such end plates shaped like bows, to compensate for the deformation due to the connecting pressure. Designing shapes to deliver only tension or compression forces into the members of the end plate can make the end plate stronger.

Although end plates were not considered to be issues when designing fuel cell systems in the past, they are now a matter of great concern for designers. Changes in materials, connecting methods, and shapes of end plates allow us to produce lighter and stronger end plates, making fuel cell systems more efficient.

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