NordDesign 2016
August 10 – 12, 2016
Trondheim, Norway

Concept selection, design methods and validation for fuel cell system thermal insulation applications operating in high temperatures

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Abstract

Solid Oxide Fuel Cell (SOFC) systems operate at high temperatures (600–900 °C) and thus thermal insulation is essential part of the system. Concept selection for the thermal insulation is pivotal to the system design as it has a significant effect on the system dimensions, instrumentation, support of components and compensation of thermal expansion. A proper thermal insulation concept should be selected at the very beginning of the project as it has strong interactions with other subsystems of the SOFC unit.

In this study a fuel cell engineering team defines a set of essential requirements for thermal insulation of SOFC fuel cell systems. Pairwise comparison methods are used to set weighting values for the defined requirements and then thermal insulation concepts are evaluated by quantitative and subjective analyses in order to identify the highest ranking concept.

The second part of this study presents design principles for systems which operate at high temperature, such as methods for compensating the thermal expansion of structural components, free thermal expansion and thermal center. Together with these principles numerical calculations can be used to verify and evaluate structural design before it is constructed.

These principles are then demonstrated by presenting the experimental test apparatus which is designed according to these rules. This apparatus is used to conduct a set of experiments in order to evaluate differing thermal insulation concepts. The test results are presented in the third part.

Together with conceptual study the experimental results prove that the proposed concept is an improvement to the prior methods of thermal insulation. Moreover, this concept is now approved by our industrial partners and it is in service in their products.

Keywords: Concept selection, design principles, fuel cell, thermal insulation, high temperature

1 Introduction

Solid Oxide Fuel Cell (SOFC) systems are used typically for stationary power generation and combined heat and power applications (Chen & Ni, 2014, Lamas, Shimizu, Matsumura, & Senda, 2013). Among competing technologies, SOFC systems have negligible particle emissions and higher electrical efficiency (Halinen, et al., 2011 & 2013, Xu, Dang, & Bai, 2013, Barelli & Ottaviano, 2014, Powell, Meinhard, Sprenkle, Chick, & McVay, 2012) in a wide power range. According to market reviews (Fuel Cell Today, 2015), market share of SOFC units has started to increase significantly over the past four years indicating that eventually the technology is reaching maturity and changing to a profitable business for system developers. Due to this, we have made this investigation in order to evaluate and test thermal insulation concepts for SOFC systems that operate at high temperatures (up to 800 °C) to accelerate the system development process.

The thermal insulation of the fuel cell unit comprises the thermal insulation material and its form and shape around the hot components and material's thermal conductivity and thickness are the most important factors affecting the efficiency of the thermal insulation. Thus, it is natural that many first generation devices relied on ostensibly simple thermal insulation methods like Individual insulation of components or Box-type insulation around the system modules containing the hottest parts (Figure 1).

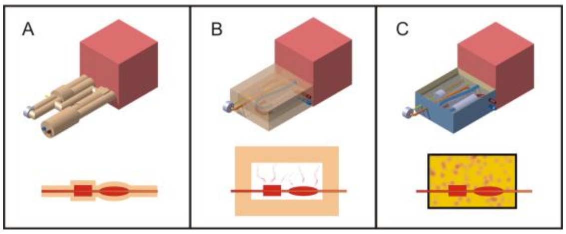

Figure 1. Insulation concepts A) Individual, B) Box-type, C) Granular insulation.

Unfortunately, both methods have drawbacks in practice. Individual insulation may not conform to changing structural dimensions caused by thermal expansion. In addition, the implementation of individual insulation is extremely time consuming which makes it unsuitable for mass production. It makes system maintenance more complicated and increases the system dimensions. Box-type insulation is another common solution which is relatively simple to design and assemble but it has also weaknesses. The most important weaknesses are the need to make numerous lead-troughs for piping, instrumentation, and conductors. These usually make thermal bridges through the insulation and thus thermal insulation is compromised. In addition, structural design becomes more complicated if there be parts within this box with lower operating temperature than what is the temperature inside the enclosure.

The main hypothesis in this study is that the loose granular thermal insulation material may outperform solid thermal insulation materials in real life situations, when system shape is complex and operating temperature is high. Solid thermal insulation materials typically have lower thermal conductivity than loose insulation materials, but granular insulation has capability to fill all the cavities and thus the effective thickness of insulation is higher. However, even with the thermal insulation total thermal loss of the system is not the sole factor that must be considered when selecting the thermal insulation concept. In the first part of this study twenty-one requirements (P. Salminen et al., 2013) are used to evaluate three different thermal insulation concepts for the SOFC Balance of Plant (BoP). The second and the third parts explain the basic design principles that were used to design and build a test apparatus to conduct experiments for these thermal insulation methods. Results of these experiments are presented at the end.

In short, this investigation aims not only to reduce the thermal losses, but also to present quick implementation solutions which cause minimal restrictions for system design. The ultimate objective is to propose a superior thermal insulation method to be adopted in the mass production of the next generation power generating units operating at high temperatures.

2 Evaluation of thermal insulation concepts

A Concept Development Support Tool (Salonen, 2004) is used for the selection of the best thermal insulation method. It is a systematical tool that is based on paired comparison method. Main steps for this systematic approach are as follows: As the first step, defining the requirements is conducted in a cooperation with a group of specialist designers of fuel cell systems from industry, research center and university (Figure 2.1 and Table 1). This must be made at the very beginning to minimize the risk of recognizing important requirements too late (Günther & Ehrlenspiel, 1999). After this the requirements are weighted using paired comparisons (Figure 2.2) by two experts.

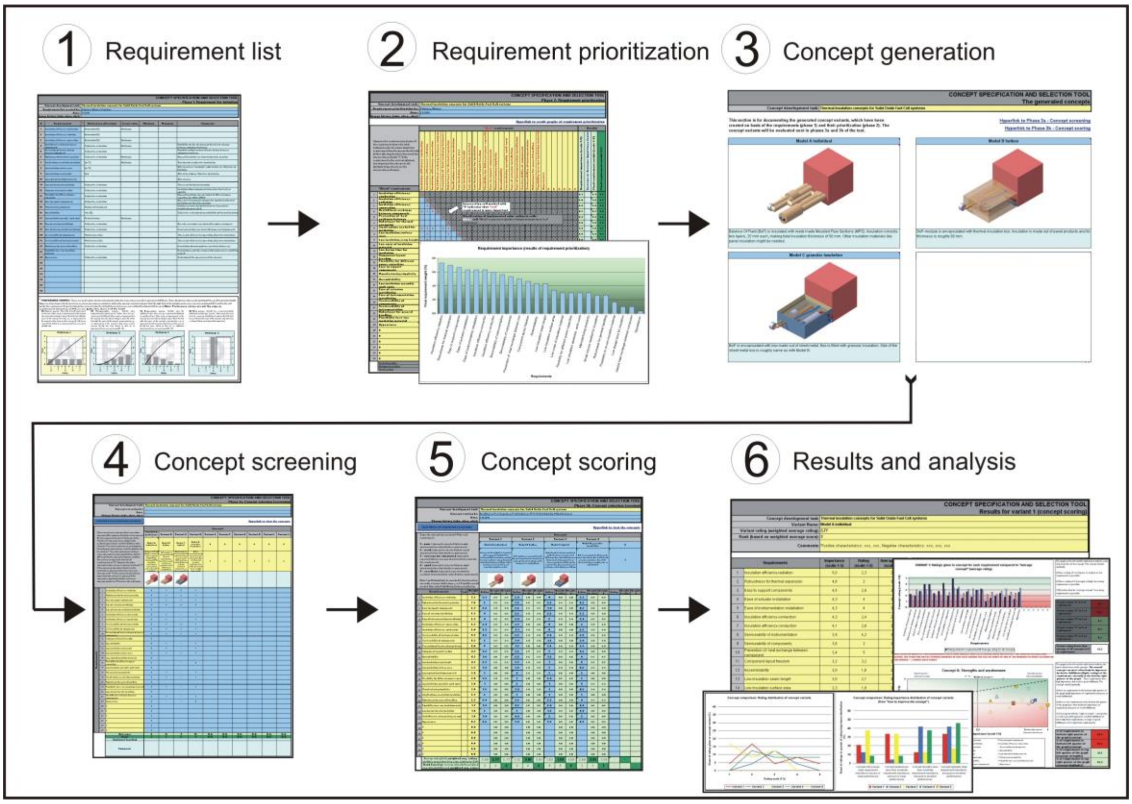

Figure 2. Process flow of the concept development support tool that was used mainly for the evaluation of the thermal insulation concepts.

Third step is the concept generation (Fiqure 2.3) and three different thermal insulation methods (Figure 1) were chosen for the evaluation. Two of these, Individual and Box-type insulation represent the traditional methods of insulation. Third, Granular insulation, represents a new method to be used for thermal insulation of a system partly or wholly. All these methods utilize microporous thermal insulation material that is processed to be either moulded, rigid or granular product. The exact specifications of these materials and these three methods can be found in Table 3 or in earlier article (P. Salminen et al., 2013).

The system module that is insulated by these methods is presented in Figure 3. It is a slightly simplified part of the system presented by Halinen (Halinen, et al., 2011) and its structural design was made by authors.

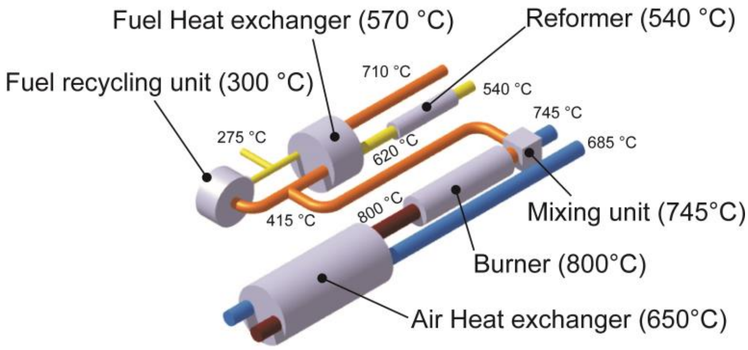

Figure 3. BoP-module components and their operating temperatures. Instrumentation, valves and actuators excluded for clarity.

Fourth step of the Concept Selection Tool is concept screening (Figure 2.4) which utilizes Pugh method (Pugh, 1996, King & Sivaloganathan, 1999). Screening is a fast method to omit worst concepts and to narrow down number of acceptable concepts for closer evaluation. In this investigation unsuitable designs were omitted at the beginning. Fifth step (Figure 2.5) is requirement scoring which was made by group of expert designers. These results are shown in Table 1.

Table 1. Detailed requirements, weighting and grading based on subjective evaluation and calculated values (P. Salminen et al., 2013).

Requirement	Weight %	INDIVIDUAL	BOX-TYPE	GRANULAR
Easy to support components	**8.7**	2.8	2.6	4.2
Ease of instrumentation installation	**8.2**	4.0	2.4	3.4
Ease of actuator installation	**8.2**	4.0	2.6	3.2
Robustness for thermal expansion	**7.8**	2.0	3.8	4.2
Serviceability of instrumentation	**7.4**	4.2	2.8	2.8
Serviceability of components	**6.9**	2.0	3.4	3.4
Component layout freedom	**6.1**	3.2	3.6	4.2
Assemblability	**5.6**	1.6	2.8	4.0
Prevention of heat exchange between component	**5.2**	5.0	1.2	3.6
Low risk for thermal loss thru seams*	**4.8**	1.9	3.1	5.0
Low amount of parts in insulation assembly*	**3.9**	1.4	3.7	5.0
Manufacturing simplicity	**3.9**	1.6	3.4	4.6
Flexibility for different power capacities	**3.9**	3.2	3.0	3.0
Low cost of Insulation material*	**3.9**	2.9	4.2	3.0
Robustness for general handling	**3.5**	2.4	2.6	4.0
Low insulation surface area*	**3.5**	3.3	3.4	3.4
Low insulation material volume*	**3.5**	3.8	3.6	2.6
Possibility to re-use insulation material	**2.2**	1.8	4.2	4.4
Usefull heat exchange between components	**1.3**	1.4	4.4	2.0
Low design time for insulation	**1.3**	2.0	3.0	4.4
Appearance	**0.4**	2.6	3.4	4.2

* = Calculated value (vs. subjective evaluation)
1 = poor (concept is expected to have poor characteristics related to the requirement)
2 = weak (concept is expected to have weak characteristics related to the requirement)
3 = average (or adequate) (concept is expected to have average characteristics related to the requirement)
4 = good (concept is expected to have good characteristics related to the requirement)
5 = excellent (concept is expected to have excellent characteristics related to the requirement)

Last step (Figure 2.6) provides results and analysis data for the comparison of the concepts. Last step also includes an option to test different values for weighting or scoring which is practical way to conduct a rough sensitivity analysis. This option proved that final results were not too sensitive to any minor changes and thus the results are reliable. The final ranking of three concepts are shown in Table 2. As a conclusion, the Granular insulation was evaluated to be the most suitable for this application.

Table 2. Averaged scoring, weighted scores and ranking for thermal insulation models. Grades are given from 0 to 5.

Model	Model C granular		Model B box-type		Model A individual	
	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
Scoring	3.74	3.73	3.20	3.05	2.72	2.92
Ranking	**1.00**	**1.00**	**2.00**	**2.00**	**3.00**	**3.00**

3 Structural design principles apparatus operating at high temperature

The Granular insulation was a highest ranking method for thermal insulation of SOFC module by the analytical Concept Selection Tool. However, there was no previous experience of utilizing this method in large scale. New experimental and fully integrated 10 kW SOFC unit was under construction but it was considered to be too risky to test a new thermal insulation method in practice with this new unit that had a tight schedule for the coming experiments. Therefore, an independent test apparatus was designed and constructed to evaluate the thermal insulation concepts. In addition, this test setup offered a possibility to test out design principles for units that are exposed to large structural displacements due to thermal expansion.

The first and the most important thing during initial system layout design is the selection of Thermal Centers. These points act as non-moving points of the structure that is susceptible to endure thermal expansion during thermal cycling. The Thermal Centers are ideal locations for placing elements such as seals and fixtures between the hot and cool modules. Section cut of the experimental system is shown in Figure 4 which demonstrates this principle in 2D-figure. The whole system is roughly three meters long and piping structure is made of temperature resistant stainless steel.

In each thermal cycle long piping connecting the heater to the hot module expands up to 15 mm. To avoid structural damages caused by this thermal expansion, the system is to be designed in a way that it be capable of free axial movements, at least in one end. In this design at one end heater and blower are mounted on linear guides that operate at room temperature. And at the other end components in the insulated box are supported by a cradle-like bed where operational temperature is 600 °C. These provide enough support for components without restricting thermal movements of the system (Salminen, Ahlgren, & Kuosmanen, 2013).

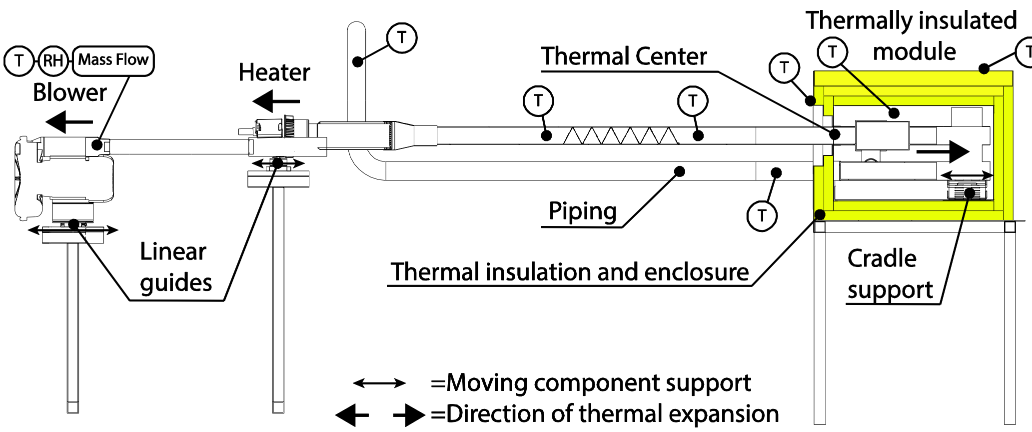

Figure 4. Example of using Thermal Center at the border between hot piping and components and cool outer enclosure of the insulated box. Here single thermal bridge acts as a structural non-moving support and as a hermetical seal between inner and outer space of thermally insulated enclosure. Instrumentation shown to present experimental setup. Thermal insulation of piping excluded for clarity.

In addition, it must be considered that components of the 3D-stuctures exposed to thermal gradients tend to become curved. Due to this, sideway dislocations should be compensated as well. In this unit there were minor sideways dislocations which were compensated by flexible support legs and piping. One common way to compensate thermal movements is to use pipe bellows, but these tend to be expensive and structurally weak parts of the piping in elevated temperatures. Thus, the amount of pipe bellows should be kept to minimum. In this design no bellows were used at all and linear guides and sliding support worked well in practice.

Finite Element thermal analysis tools were utilized to verify the correct operation of the system. When systems structure becomes complicated, logical thinking is helpful but cannot substitute numerical calculations (Salminen, Ahlgren, & Kuosmanen, 2013).

4 Methods and theory for experimental testing of thermal insulation concepts

An experimental device was used to test three thermal insulation concepts: Box-type insulation, Granular insulation, and Hybrid insulation. For experimental testing Individual insulation concept was substituted by Hybrid insulation concept, because it had the lowest scoring in the ranking. A sheet metal enclosure is built to contain thermal insulation material and hot system parts. To increase the design flexibility the casing walls are attached to each other by bolts and nuts. The length, width and height of the casing are 518, 406 and 350 mm, respectively. It is painted in mat black to facilitate good quality of thermal imaging inspection. The test setups are shown in Figure 5.

In the Box-type insulation concept experiment two layers of 25 mm thick insulating panels with reinforced edges are glued to the casing's walls. Then casing's walls are attached to each other to build an insulating box surrounding the hot components. In the Granular insulation concept experiment the top plate of the casing is removed to provide access to the inner space. The inner space is fully filled with the granular insulation material up to the top of the casing. Then the top wall is fixed in place. Hybrid insulation concept is the combination of Box-type and Granular insulation concepts to combine good thermal properties of the panel insulation with cavity filling properties of the granular insulation. The insulation material properties are presented in Table 3.

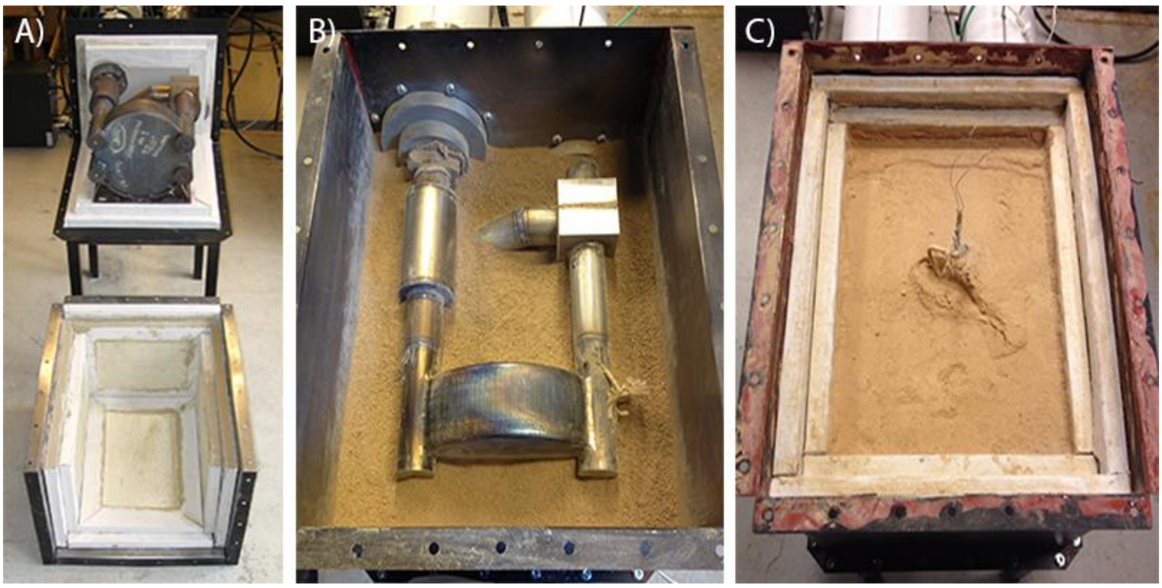

Figure 5. Test setup for: a) Box-type insulation, b) Granular insulation, c) Hybrid insulation. Granular material is Promat Freeflow® 220 and panel is Promalight 1000X.

Table 3. Thermal properties of the thermal insulation materials.

Material	Thermal conductivity, κ [W/M·K]	Used at
Promalight 1000X	0.023 @200°C–0.036 @800°C	Panel insulation and bottom plate
Promat FreeFlow 220 kg/m³	0.026 @200°C–0.064 @800°C	Granular and Hybrid insulation

Experiment setups are planned to simulate a complete thermal insulation in conditions as similar as possible to a real working unit. Hence the hot air (600 °C) is flowing through the system instead of using stationary heating resistors. As the system makes no external work, the thermal loss is equal to change in the enthalpy of the flowing air. The first law of thermodynamics (Clausius & Rankine, 1850) is used to determine the thermal loss of the enclosed system. The air volume flow, the temperature and the pressure are measured from the air intake and the outlet of the BoP module and the system thermal loss is calculated based on these measurements. Starting from the total energy change of the system, required equations are as follows:

$$\Delta E = E_{in} - E_{out} \qquad \textbf{Eq 1}$$

When the system reaches the steady state, i.e. the temperature becomes stable, the energy change is zero at system level (ΔE=0). The experimental apparatus is a closed system. The energy input to the system is in the form of hot air, and the energy loss is the energy content in the exhaust air and the thermal loss through the insulation of the system. Thus, the following equation is formed:

$$\dot{q}_{air\ in} - \dot{q}_{air\ out} - q_{thermal\ loss} = 0 \qquad \textbf{Eq 2}$$

The pressure change in the system as well as the kinetic energy of the air flow are negligible in this apparatus, consequently leading to the following equation (Incopera, DeWitt, Bergmann, & Lavine, 2007):

$$q_{thermal\ loss} = \dot{m} \cdot c_p \cdot (T_{out} - T_{in}) \qquad \textbf{Eq 3}$$

where $q_{thermal\ loss}$ [W] is BoP-module´s thermal loss due to conduction, convection and radiation, $\dot{m}$ is mass flow [kg/sec] and c_p is specific heat capacity [J/(kg•K)] of dry air at the atmospheric pressure. The specific heat capacity of the air is affected by the temperature, pressure and water vapour content of the air.

Measurement instruments descriptions and accuracies are presented in Table 4 and their locations are illustrated in Figure 4. In addition, laboratory condition may have an effect on measurement accuracy. However, this error is insignificant compared with instrumental errors due to controlled laboratory conditions.

Table 4. Measurement instruments and accuracy.

Instrument	Part Number	Description	Accuracy
High-Accuracy Thermocouple Module	NI 9214	16-Channel Isothermal Thermocouple Input Module	0.5 °C
Thermocouple	JUMO 91250/32-1043-1.5	Operating temperature: -200 to +1200 °C Tube diameter and length: 1.5 and 200 mm	±2.5 °C or ±0. 75 %
Thermocouple Wire	WATLOW K20-2-350 SPECIAL	K-type	0.5 °C or ±0.4 %
Pressure Sensor	*Jumo 402005/000-441-409-294 and MR-100 flowmeter*	Differential Pressure Sensor and measurement ring	4 %
Humidity Meter	*Fluke 971*	Electronic capacitance polymer film sensor.	±2.5 % RH

5 Results

5.1 Assembly

Thermal insulations assembly was done manually by one person and installation time was measured. The time spent for installing Granular insulation, Panel insulation and Hybrid insulation was 0.5, 39.5 and 40 hours, respectively. Installing the Panel and Hybrid insulations was time consuming. Because cutting of panels, edge reinforcement with cloth and fitting panels in the casing involve a lot of effort. The installation time could be reduced by using pre-cut panels in the production scale, but it will be still significantly slower than insulation with granular material. The panel insulation material cost was 30 % higher than the granular insulation material cost. Accordingly, the Hybrid insulation was the most time consuming and the most expensive solution in comparison.

5.2 Thermal loss

The thermal loss of the thermal insulation concepts is calculated based on the measured parameters at the steady state at 600 °C. The system was considered to be in the steady state when thermal loss change was below 1 W/h for one hour. This took 14 to 18 h for the concepts and the measurements were repeated three times in order to check repeability of experiments and two times after this. The results are shown in Figure 6 and Table 5. According to the presented results, the lowest heat loss is achieved with the concept utilizing granular insulation material. Hybrid insulation is close second, its result being within measurement uncertainty limits with the granular insulation.

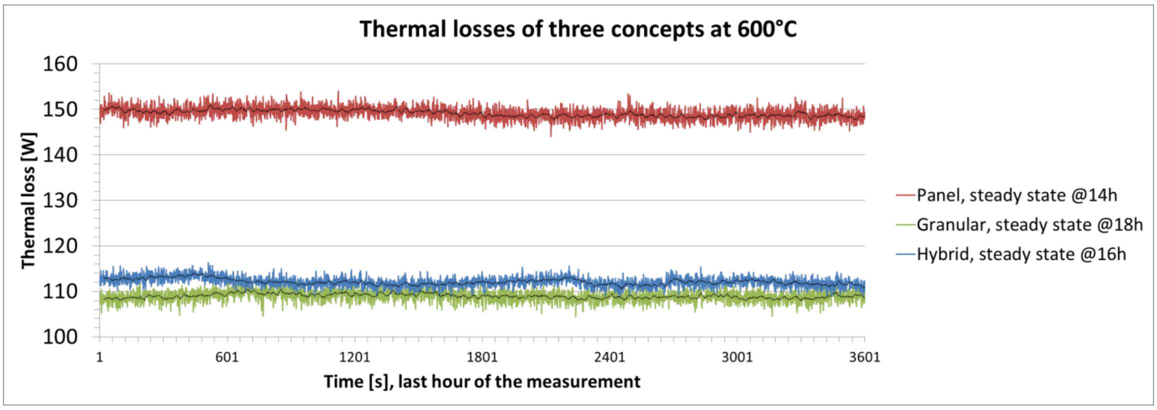

Figure 6. Thermal losses of three concepts in steady state at 600 °C.

Table 5. Measured thermal loss of the concepts.

Concept	Panel insulation	Granular insulation	Hybrid insulation
Thermal loss	149W ±10 W	110 W ±10 W	112 W ±10 W

5.3 Inspection of insulation materials after the experiments

Thermal insulation might be removed several times during the system lifetime due to the system maintenance. Therefore, after the experiments the thermal insulations were removed and inspected. The panel insulation was in a good shape after experiments. But panels become fragile and vulnerable after thermal cycling. If they are handled carelessly or heavy shocks are applied to the enclosure the panels may crush or crack. In larger units handling of the enclosure becomes difficult due to the size and weight of the enclosure.

The removal of the granular insulation from Granular and Hybrid insulations was fast and non-dusting when insulation material was vacuumed out of the casing using an industrial dust extractor system with cyclon pre-separator. During the removal process it was noted that granular insulation solidifies slightly during thermal cycling. This is beneficial, as it forms a solid block surrounding the components that resist compaction in movements of the insulation material during the operation. Inspection did not reveal any cracks in this block due to thermal cycling or thermal expansion. During installation and removal the granules slightly crush and be ground and the density of the material increases. Used insulation material is collected in a cyclon separator for later use. However, thermal properties of the used granular insulation material was not investigated in this research and only new material was utilized in the experiments.

6 Discussion and conclusions

The results of this study prove that Granular insulation is the superior method compared with Hybrid-, Panel- and Individual insulation methods in our application. It simplifies the design of the system by reducing constraints that thermal insulation produces. In many cases, system size can be reduced and lower thermal insulation cost is achieved. In addition, Granular insulation offers fast installation and removal of the insulation material during manufacturing, maintenance, and recycling.

In experimental tests, Granular insulation methods achieved lower total heat loss than Box-type insulation. The thermal loss of the Hybrid insulation was equivalent to the pure Granular insulation, but it adds unnecessary design complexity and cost due to time consuming installation process and thus pure Granular insulation is recommended over Hybrid insulation.

The thermal insulation concept has a great effect on the system thermal loss. However, attention must be given to details such as lead-throughs for pipes, instrumentation and electricity conductors. With the efficient thermal insulation of the enclosure the thermal loss of the component supports and lead-throughs present roughly half of the total heat loss. This was calculated using FEM model of the experimental device and FEM model results were verified by thermal imaging. However, these are out of scope of this article, but will be published shortly in a suitable journal.

In conclusion, this study has recognized the Granular insulation as a suitable thermal insulation method for SOFC systems. Future research and development should focus on reducing the thermal loss of the lead-throughs, as there are next major possibilities to make reductions to thermal loss of the systems. In addition, during the theoretical and experimental part of the study it is found that absorbed moisture in insulation material might cause corrosion or decrease thermal insulation properties (Bouquerel, Duforestel, Baillis, & Rusaouen, 2012). In future, this should be further investigated especially if high temperature systems are manufactured or operated in humid environments.

This study also proved that analytical system development methods lead to a thorough understanding of the system, which is helpful for designing, constructing and testing the experimental setup. As a final note, due to this study, our partners in research and industry have succesfully implemented the results of this study into their systems.

Acknowledgements

This research is part of the RealDemo –project, which is funded by Finnish Funding Agency for Technology and Innovation (Tekes) and the Graduate School of Concurrent Mechanical Engineering coordinated by the Tampere University of Technology, Finland. The project was coordinated by the VTT Technical Research Centre of Finland. We acknowledge project coordinator M. Halinen (VTT) for the useful discussions and V. Kyyhkynen (Convion Ltd) for offering their valuable time.

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