Abstract—This study evaluates three different thermal insulation concepts for the Balance of Plant (BoP) components of a Solid Oxide Fuel Cell (SOFC) system. Improvements in this field are needed in order to enable economical mass production of systems with higher integration level. Thermal insulation concept sets a lot of constrains for system design and it can be a costly part of the system when considering time used for design and assembly.

A fuel cell engineering team has defined a set of requirements that are essential for thermal insulation. Important aspects of these requirements are discussed in detail. Pairwise comparison methods and concept development support tool is used for scoring and ranking of the concepts. For the evaluation a 10 kW research unit has been used as a baseline, but results can be utilized within different power classes.

Granular thermal insulation concept for the BoP components and piping received the highest ratings from the fuel cell engineering team according to requirements. Box style insulation and individual thermal insulation of components and piping were ranked the second best.

1. INTRODUCTION

This study evaluates three thermal insulation concepts for Solid Oxide Fuel Cell (SOFC) systems. SOFC systems operate at high temperatures (650–900 °C) and thermal insulation is essential part of the unit [1]. It has a pivotal effect on the system design. Selection of thermal insulation concept influences system dimensions, support of components, heat exchange between components and other subsystems. Interactions between thermal insulation, system components and system structure are complex, and not every impact can be evaluated by intuition only. Number of different interactions is high and analytical evaluation of these effects is useful for successful system design.

Efficient thermal insulation has several benefits. For example, minimum temperature must be maintained when the system is idling or running with partial loads. As a result, low thermal losses save fuel, thereby providing better overall efficiency. Efficient thermal insulation can also provide fast start-ups from standby to full power output. In Combined Heat and Power (CHP) systems good thermal insulation increases thermal efficiency.

A suitable insulation concept can provide further freedom for piping and component design, helping to reduce the space needed for insulation. Experimental units typically have an individual thermal insulation around components and piping. Insulation panels, blocks or blankets need space-allowance for assembling, which can increase system size and piping lengths. In small units this may lead to significant thermal losses, due to the relatively large surface area of the thermal insulation. Additionally, increased piping length or reduced piping size may increase pressure losses. While these losses are relatively small, they could have an effect on needed air blower power.

Fuel cell units also have an effect on its surroundings. Well-designed thermal insulation reduces surface temperatures, which is essential for the safety of the system and its users. Smaller temperature variations in the system may increase system structure lifetime by reducing thermal cycles and shocks [2]. Lower thermal losses reduce heat stress to the space where the system is operating, thus reducing the need for energy consuming ventilation or excess cooling.

Several researchers have investigated thermal insulation for SOFC units. Spinnler et al. [3, 4] examined multilayer thermal insulations for high-temperature fuel cell applications. Damm and Fedorov [5] investigated radiation heat transfer in SOFC materials and components. They concluded that radiation phenomena are of great interest and importance for the SOFC systems, not only from a fundamental perspective but also from a systems design point of view. Suitable insulation materials are also studied for uses other than fuel cells. The use of granular silica based insulation has been studied for low temperature applications. It can be used as a substitute for polyurethane in refrigerators and house walls [6, 7]. One study concluded that the thermal performance of aerogel granules was similar to aerogel monoliths at certain temperature and pressure conditions [8].

Apfel et al. [9] have studied thermal management strategies. They investigated thermal start-up behaviour and thermal management for SOFC units. According to them, large thermal gradients must be avoided. This can be done by selecting right system design and control strategies. In addition, cooling down of the system should be avoided if instant operation is desired. To achieve this, one must choose suitable insulation materials.

When designing SOFC system, one must be aware of different possibilities and choose accordingly. Chosen concept will have central effect on system design. This research investigates new solutions and applications for thermal insulation on SOFC systems. Traditionally there have been few different solutions for thermal insulation. The comparison of concepts is complex, and there is a tendency to use thermal insulation concepts which have been used previously. Systematic pairwise comparison methods and the
concept development support tool were used in this research to reveal the differences between concepts. Therefore, we were able to combine numerical data and subjective analysis to define the optimal concept.

II. METHODS

A. 10 kW Research Unit

As a baseline for research we have chosen BoP-module of the existing and working 10 kW research unit [10]. In this research we use its components, properties and design layout as a starting point and it is also a point of reference. Dimensions and component sizes are verified to work in the integrated SOFC system with enough room for the instrumentation needed in the experimental unit. This study concentrates mainly on thermal insulation, not on mechanical design of system. To make different case examples comparable, we do not alter mechanical design too much, even if it might not be optimal for different cases.

The SOFC-system can be divided into three zones (Fig. 1.) with different temperatures. Cool components (<60 °C) include fresh air blowers, electronics, measurement devices and actuators. Medium hot components (60–550 °C) include heat exchangers, reformers, valves and fuel recycle unit. Hot components (>550 °C) include burner and stack module. High temperature components must be isolated thermally from the surroundings to minimize thermal loss and heat stress to surroundings. This will secure safe, reliable and efficient operation for the power generating unit. Allowing cool components like electronics to run in too warm environment could result in degradation [11].

B. Thermal Insulation Concepts

Three different concepts (Fig. 4.) were designed with 3D-engineering program (Catia®). All concepts are using microporous insulation material, but in different forms. Concept A is the reference point, since this insulation concept was used for 10 kW research unit. The insulating method in this concept prevents direct thermal interaction between system components. Insulation material in the system is Microtherm™ moulded pipe sections. Single pipe section has a thickness of 25 mm. With two layers the total insulation thickness in Concept A is 50 mm. In 400 °C mean temperature the insulation material has a thermal conductivity of 0.0244 W/m·K. Temperatures of the 10 kW research unit were used in modelling (Fig. 3). Based on the modelling a thermal loss of about 600 W in concept A was acquired. This result will later be used as a reference point for calculating insulation thicknesses in concepts B and C.
The insulation box in Concept B surrounds all the hot components in one enclosure which is made of Microtherm™ microporous rigid panel product. This concept allows thermal interaction between components inside the insulation box because there is no thermal insulation separating the components. This leads to significant space savings but also means the working allowances between BoP components are minimal. The piping and component layout of the concept were altered in comparison to concept A in order to achieve more efficient use of space and smaller outer dimensions.

Concept C is a box made of sheet metal with its interior filled with granular insulation material. BoP construction is identical to Concept B.

Insulation thicknesses in concepts B and C were calculated by assuming the same thermal loss as in concept A. Thermal conductivities for the insulation materials in 400 °C mean temperature were B: 0.0244 W/m·K and C: 0.048 W/m·K. For the calculation of the insulation thickness the piping and components were given correct operating temperatures in FEM according to real world system (Fig. 3). In concept C the insulation thickness is defined as a minimum value between the sheet metal walls of the box and the hot components inside it. The calculated insulation thicknesses as well as total insulation material volumes are shown in Table 1.

Two overlapping layers of insulation panel are used in concept B in order to prevent thermal loss from seams. Thickness of single panel in concept B is 30 mm. It is also a standard thickness from manufacturer. Maximum dimensions for single panel were selected to be 1000 mm x 500 mm because it suits the dimensions of the system and larger panels would be more fragile. The dimensions of the insulation parts also have an effect on the total insulation parts count in each concept (Table 1). Sheet metal is used as support structure and as an outer surface for the insulation box in concepts B and C although this is not visible in Fig. 4b.

C. Concept Development Support Tool

A Concept Development Support Tool [13] has been 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: At the start of the design process a list of requirements is done (1. in Fig. 5). This must be made at the very beginning to minimize the risk of recognizing important requirements too late [14]. After this the requirements are weighted using paired comparisons (2. in Fig. 5). Requirements are presented in chapter 2.4. In this study pairwise comparison was made by two expert designers, so weighting values are based on their experience on designing thermal insulation for BoP of the 10 kW research unit. Paired Comparisons is a basic method that is used for example in Quality Function Deployment (QFD) [15] and Analytical Hierarchy Process (AHP) [16, 17, 18]. Paired comparison means that every requirement is compared to all the other requirements. The requirement that is most times considered more important than the other requirements, receives highest importance on weightings.

Third step is the concept generation (3. in Fig. 5). There is no direct method for the creation of the concepts in this research. Basically three different style designs were chosen for the evaluation. These designs were chosen to represent typical thermal insulation methods which are used in large stationary SOFC systems. Fourth step (4. in Fig. 5) is concept screening which utilizes Pugh method [19, 20]. Screening is fast method to drop off worst concepts and to narrow down number of better concepts for closer evaluation. Fifth step (5. in Fig. 5) is concept scoring. Last step (6. in Fig. 5) 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.

### Table 1

<table>
<thead>
<tr>
<th>Concept</th>
<th>Insulation thickness [mm]</th>
<th>Insulation seam length [m]</th>
<th>Insulation surface area [m²]</th>
<th>Insulation material volume [m³]</th>
<th>Parts in insulation assembly</th>
<th>Relative insulation material cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>50</td>
<td>22.0</td>
<td>3.7</td>
<td>0.14</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>60</td>
<td>13.8</td>
<td>3.5</td>
<td>0.17</td>
<td>36</td>
<td>0.40</td>
</tr>
<tr>
<td>C</td>
<td>minimum 60</td>
<td>0.0</td>
<td>3.5</td>
<td>0.28</td>
<td>1</td>
<td>0.97</td>
</tr>
</tbody>
</table>
D. Requirements and Scoring

Twenty one requirements were chosen for evaluation of the models. The selection of these requirements was based on the experiences from the design and construction phase of the 10 kW research unit. Five of these requirements could be scored with numerical values that were measured from 3D-models. The remaining 16 requirements were scored by subjective evaluation by six expert fuel cell system designers from Aalto University, VTT Technical Research Centre of Finland and Wärtsilä Finland.

Scoring sheet was made for the subjective evaluation. Following scale was used for the scoring:

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 (concept is expected to have avg. 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)

In this research, averages of these scorings were used for calculation of results. However, design team members may have widely differing opinions about the requirement importance and scoring. Discussions and fine tuning of scoring between team members is possible in this step if opinions vary greatly.

D. A. Requirements Based on Numerical Values

“Low Risk for Thermal Loss Thru Seams” is favourable for a concept. Thermal loss through the seams can be significant if parts of the thermal insulation move apart due to thermal expansion, vibration, careless assembly or other reasons. In concept A the amount of seam in the insulation assembly is proportional to the total piping length in the system. In concept B the amount of seam corresponds to the volume of the insulation box and sizing of the panel used. Concept C does not contain seams, because the insulation is in the granular form and it could deform when piping and components have thermal expansion. Seams of the outer surface of the thermal insulation are used to define scoring for the concepts. The seam lengths are shown in Table 1. However, thermal insulation design has an effect on how harmful the seams are. One must try to design thermal insulation in such way, that the gaps could not form in use during thermal cycling.

“Low Insulation Surface Area” is very favourable for a concept. It has direct effect on thermal losses. In this case, the insulation surface areas are mostly affected by the different layouts. The length of piping will increase the amount of insulation area more when moulded pipe sections are used if compared to box-type insulation. In addition to thermal losses, the surface area also effects on the amount of possible surface finish materials such as paint, as well as its reactions with surrounding atmosphere. Total insulation surface areas are shown in Table 1.

“Low Insulation Material Volume” is also advantage for system design. Small insulation volume allows more space for other components inside the system enclosure. Insulation material volumes are shown in Table 1.

Insulation material costs were calculated by using market prices of year 2011 for the insulation materials with the needed material volumes. The requirement is called “Low Cost of Insulation Material.” Moulded pipe sections used in concept A are the most expensive material regarding its unit price (€/m³) and granular insulation is roughly half of its price. The rigid panel product in concept B is one third of the price of moulded pipe sections. Relative insulation material costs for each concept are shown in Table 1.

“Low Amount of Parts in Insulation Assembly” helps to cut assembling time and labour costs. Amount of parts in insulation assemblies in the concepts are shown in Table 1. Low amount of parts is a favourable quality.

D. B. Layout Requirements

“Component Layout Freedom” is important for system design. This means low insulation based restrictions for chosen concept. For example concept A includes a one type of restriction where designer must leave enough installation allowance for insulation. This means that there needs to be at least 120 mm installation allowance between the piping components if moulded pipe sections are used to insulate both piping components individually. Models B and C have better freedom for component layout in this respect.

“Ease of Actuator and Instrumentation Installation” describes how easily a particular insulation concept allows the typical components to be installed. For example the need to do handwork like cutting and gluing of the insulation material makes installation more difficult. “Manufacturing Simplicity” and “Low Design Time for Thermal Insulation” also define how advantageous the design is.

“Ease to Support Components” is important in respect of avoiding thermal losses. Components can weight more than several hundred kilos in the case of larger units and these components need to be mechanically supported. Supports tend to produce thermal bridges through the insulation. In addition, this requirement could have an effect on system design and costs.

“Flexibility for Different Power Capacities” indicates that the concept can be scaled up for larger system dimensions.

Some concepts can more easily be designed to have a good “Assemblability” than others. This could have an effect on different costs ranging from design and manufacturing to assembly labour.

D. C. Physical Requirements

“Robustness for Thermal Expansion” evaluates how well insulation can adapt to thermal expansion of the structure during thermal cycles. In optimal design this movement should not cause any mechanical stress, thermal leakages or other problems for insulation. “Useful Heat Exchange Between Components” and “Prevention of Heat Exchange Between Components” were also evaluated and weighted. The meaning of these is to connect or isolate components thermally. Excess heat can be utilized for pre-heating or reforming purposes [21]. Respectively some components are better to be isolated thermally, especially if components performance in being studied and the effect of other components should be eliminated.
**D. D. Consumer Perspective**

“Serviceability of Components and Instrumentation” is a requirement that is significant for the end user of the product. When servicing is performed there is a need to remove some parts of the insulation assembly and then rebuild them. In this situation the “Possibility to Re-use Insulation Material” is also beneficial. “Robustness for General Handling” can make installation work faster and easier.

The “Appearance” of the system has been weighted as the least important requirement but might still be significant to some users.

### III. RESULTS

Selection between the three concepts was made by using detailed evaluation data which was produced with the product development tool. Initially weighting values were defined and the requirements were graded. The results of these steps are shown in Table 2.

Two fuel cell design experts made the pair-wise comparison of the requirements by using product development tool. Requirement weightings are based on this evaluation and result are shown in Table 2. After this, six expert designers did the evaluation of the three concepts. This scoring is shown in Table 2 for all the requirements and concepts.

### TABLE II

**DETAILED REQUIREMENTS WEIGHTING AND GRADING BASED ON SUBJECTIVE EVALUATION AND CALCULATED VALUES**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Weight %</th>
<th>INDIVIDUAL BOX-TYPE GRANULAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease in support components</td>
<td>8.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Ease of instrumentation installation</td>
<td>8.2</td>
<td>4.0</td>
</tr>
<tr>
<td>Ease of actuator installation</td>
<td>8.2</td>
<td>4.0</td>
</tr>
<tr>
<td>Robustness for thermal expansion</td>
<td>7.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Serviceability of instrumentation</td>
<td>7.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Serviceability of components</td>
<td>7.6</td>
<td>2.0</td>
</tr>
<tr>
<td>Component layout freedom</td>
<td>6.1</td>
<td>3.2</td>
</tr>
<tr>
<td>Accessibility</td>
<td>5.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Prevention of heat exchange between component</td>
<td>5.2</td>
<td>5.0</td>
</tr>
<tr>
<td>Low risk for thermal loss thru seams</td>
<td>4.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Low amount of parts in insulation assembly*</td>
<td>3.9</td>
<td>1.4</td>
</tr>
<tr>
<td>Manufacturing simplicity</td>
<td>3.9</td>
<td>1.6</td>
</tr>
<tr>
<td>Flexibility for different power capacities</td>
<td>3.9</td>
<td>3.2</td>
</tr>
<tr>
<td>Low cost of insulation material</td>
<td>3.9</td>
<td>2.9</td>
</tr>
<tr>
<td>Robustness for general handling</td>
<td>3.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Low insulation surface area*</td>
<td>3.5</td>
<td>3.3</td>
</tr>
<tr>
<td>Low insulation material volume*</td>
<td>3.5</td>
<td>3.8</td>
</tr>
<tr>
<td>Possibility to re-use insulation material</td>
<td>2.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Useful heat exchange between components</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Low design time for insulation</td>
<td>1.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Appearance</td>
<td>0.4</td>
<td>2.6</td>
</tr>
</tbody>
</table>

* = Calculated value (see 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)

From these results Product Development Tool calculated the final results by aggregation and averaging. In addition, weighting values were used to calculate the weighted scoring. In this final step Concept C which is based on granular insulation got the highest rank in the evaluation (Table 3).

Overall performance was good and concept did not have any clear drawbacks. Concept B (box-type) got the second place in ranking and concept A was third. However, when weighting and requirement importance is added to scoring, concept A (Solo) came close. Thus, if important decisions are made between concept B (box-type) and concept A (Individual) and based on this exact evaluation, it is recommended to make another evaluation round based on some other multiple-criteria decision support (MCDS) method. One example of these methods is Analytical Hierarchy Process (AHP) [16, 18] which gives bigger differences between concepts [12]. AHP has received criticism, but it could be used as supportive method.

### TABLE III

**AVERAGED SCORING, WEIGHTED SCORES AND RANKING FOR THERMAL INSULATION MODELS. GRADES ARE GIVEN FROM 0 TO 5. THESE NUMBERS ARE CALCULATED WITH CONCEPT SELECTION TOOL [13].**

<table>
<thead>
<tr>
<th>Model</th>
<th>Model C granular</th>
<th>Model B box-type</th>
<th>Model A Individual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating</td>
<td>Weighted score</td>
<td>Rating</td>
<td>Weighted score</td>
</tr>
<tr>
<td>Scoring</td>
<td>3.74</td>
<td>3.73</td>
<td>3.20</td>
</tr>
<tr>
<td>Ranking</td>
<td>1.00</td>
<td>1.00</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Generally speaking subjective evaluation results were consistent. All independent evaluators gave similar grading and average number represents general opinion well.

The concept specification and selection tool includes a function to test how results change according to modifications on requirement weighting and concept scoring. This function enables us to test for possible errors in problem formulation or to test effect of possibly unfair requirements selection. We found that evaluation methods used in this evaluation are quite robust, and similar results could be achieved even if input data is altered to some extent. Relatively low weighting on values does not raise any single criteria to too high importance. This test function can also be used to fine tune the results if new important findings are made during the process.

### DISCUSSION

Application of this research and its results on other unit sizes could be done, but one has to take into account the scaling rules. In addition, every decision support method and its results have strong correlation on how problem is described and how boundary conditions and requirements are defined.

#### E. Effect of unit size and scaling

10 kW research unit has been used as a baseline for this research. To some degree this evaluation can be used for larger or smaller units. This specific research unit has relatively low power to size ratio and a lot of space is reserved for instrumentation. This means that it is possible to build a commercial unit of 50 kW or more with similar outer dimensions and amount of thermal insulation.

Rules of scaling must be applied when designing larger units. For example some components generate or require heat in proportion to volume, while the ability to dissipate heat into the environment scales relative to surface area. Larger components generate more heat, but thermal loss from surface is smaller in relative sense when compared to small components. This is important aspect with concept B, box-type. Larger volume components are not as strongly affected by dissipation or absorption of heat from surface. This could enable the use of shared interior space of the thermal insulation. Smaller components with relatively larger surface area could be disturbed by absorption or dissipation of heat in similar settings. Despite the chosen insulation concept, small power generating units are more dependent on good thermal...
insulation than larger units in terms of thermal efficiency. Basic scaling equations are shown below in equation 1.

\[
(ratio \ of \ lengths)^3 = (ratio \ of \ areas)^{1/2} = (ratio \ of \ volumes)^{1/3}
\] (1)

Free space inside the BoP-module can be a critical factor for granular insulation. Empty space between components must be minimized to reduce need for insulation material. System design has to be compact to reduce volume, surface area and heat dissipation. Compact and light unit is quick to start and responds to control faster. In contrast large thermal mass will cause slow response.

Power class also has an effect on integration or separation of the BoP and stack modules. Smaller units (<20 kW) need more thermal integration because heat loss in these units can potentially be relatively large compared to electrical output. In these cases stack and its compression system could be incorporated to BoP-module. In larger systems (>20 kW) stack might well be independent module, because power and size ratio makes thermal losses relatively less important.

**CONCLUSIONS**

The results from this study show that Concept C (granular insulation) can be considered a new alternative for thermal insulation of a SOFC system. Quick insulation work and flexible component layout are benefits, as well the possibility to use one bulk material for thermal insulation. These features could provide cost-effective mass production and relatively easy maintenance work. The insulation material could be vacuumed out of the box and blown back after maintenance is done. Disadvantages include lower thermal resistance and a larger volume of the bulk material.

Concept A (individual insulation) and Concept B (insulation box) were regarded as the second most effective alternative. The insulation box obtained a higher score in evaluation, but the weighted points were not much higher than with individual insulation. The difference between these two is small in this kind of general concept comparison. If using different weighting criteria, individual insulation might work better for research units, because it blocks the thermal exchange and interaction between components. This is beneficial when the component is tested and it is validated for modeling purposes. Furthermore, individual insulation provides also straightforward instrumentation assembly and maintenance. This concept has its weaknesses as the assembly involved is time consuming and costly and thus not suited for mass production.

Concept B (insulation box) offers relatively simple and effective thermal insulation method, which could be suitable for mass production. However, box-style insulation creates a hot thermal zone inside the insulation. This could be a disadvantage, because some actuators, instrumentation devices and components such as blowers cannot operate within the high temperatures of this thermal zone. Thus, these components must be located outside of the insulation. In addition, making hot lead-through connections through thermal insulation is challenging. Furthermore, box seams and openings must be designed with precision and attention to details to avoid unnecessary thermal leaks.

One difference between Concepts A and B might be found in the flexibility to scale up to different power levels. Small units have smaller components, which are more easily affected by thermal variations in common space inside the insulation box. Larger-volume components tolerate larger thermal variations in the surrounding environment and can be fitted in to common box-style insulation. Thus, larger and mass-produced appliances could benefit from box-style insulation and the larger amount of work needed in detail design can be reasoned.

A hybrid insulation assembly between Concepts A (individual) and B (insulation box) could also be constructed. It could be seen as a compromise between these two concepts. Hybrid insulation could be used for certain components of the system, but as a primary thermal insulation it is not a good design. This is because of complicated assembly and the large amount of insulation materials and parts which are needed for the thermal insulation.

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