Investigation into the Heat Up Time for Solid Oxide Fuel Cells in Automotive Applications

by

Andrew Michael Beney

A Thesis
presented to
The University of Guelph

In partial fulfilment of requirements
for the degree of
Master's in Applied Science
in
Engineering

Guelph, Ontario, Canada
© Andrew Beney, August, 2018
ABSTRACT

INVESTIGATION INTO THE HEAT UP TIME FOR SOLID OXIDE FUEL CELLS IN AUTOMOTIVE APPLICATIONS

Andrew Beney
University of Guelph, 2018

Advisor: Dr. Ryan Clemmer

In this study, the heat up times for an SOFC are investigated looking at temperature gradients and thermal stress to determine if the heat up times are competitive for automotive applications. Different heat up rates are investigated for both single channel and dual channel scenarios. For both scenarios, the set temperature difference heat up methods produce the highest temperature gradients initially, while drastically reducing within 10-15 seconds. The 100 K maximum temperature difference method shows the most promising heat up times of 600 and 273 seconds for single channel and dual channel heating respectively and maximum temperature gradients of 3810 K/cm and 1621 K/cm. For comparison, the 2 K/s ramp rate produced temperature gradients of 1138 K/cm and 133 K/cm with heat up times of 469 and 335 seconds for the single and dual channel studies. The thermal stress model is heavily influenced by residual stress, with the thermal stress being around 550 MPA for the dual channel studies, and 10-20 MPa when residual stress is neglected.
ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Clemmer for allowing me to pursue this degree. Thank you for your support and motivation to finish this project, especially when I was accepted into law school.

I would also like to thank our funding partners Linamar and OCE TalentEdge. With the financial support I was able to pursue an MASc.

Thank you to all my friends and family who supported me throughout this journey. Your words of encouragement and support helped me throughout my research.
# TABLE OF CONTENTS

Abstract .............................................................................................................................. ii

Acknowledgements ........................................................................................................ iii

Table of Contents ............................................................................................................ iv

List of Tables ....................................................................................................................... vii

List of Figures ..................................................................................................................... viii

Nomenclature ...................................................................................................................... xii

Greek Symbols ..................................................................................................................... xiii

1 Introduction ...................................................................................................................... 1

2 Objectives ......................................................................................................................... 4

3 Literature Review .............................................................................................................. 5

  3.1 Start-up Times for APUs .............................................................................................. 7

  3.2 Start-up Times for Tubular SOFCs .............................................................................. 7

  3.3 Current SOFC Models ............................................................................................... 9

  3.4 Models Focusing on Heat-up and Start-up ................................................................. 14

  3.5 Models Incorporating Start up and Thermal Stress ................................................... 19

4 Current Model Overview ............................................................................................... 24

  4.1 Modeling Principles Used ......................................................................................... 24

    4.1.1 Laminar Flow ..................................................................................................... 24

    4.1.2 Heat Transfer ..................................................................................................... 25

    4.1.3 Custom Equations for Inlet Conditions and Stop Conditions Used in Model 27
4.1.4 Thermal Stress.............................................................................................................28
4.2 Geometry.........................................................................................................................30
4.3 Materials........................................................................................................................34
4.4 Meshing..........................................................................................................................36
4.5 Model Validation.............................................................................................................39
5 Single Channel Results ....................................................................................................41
  5.1 Introduction...................................................................................................................41
  5.2 Results/Discussion..........................................................................................................43
    5.2.1 Set Inlet Temperature..............................................................................................43
    5.2.2 Maximum Temperature Difference vs Set Temperature Heat up Rate...........48
  5.3 Conclusion....................................................................................................................60
6 Dual Channel Study..........................................................................................................60
  6.1 Introduction...................................................................................................................60
  6.2 Results/Discussion..........................................................................................................61
    6.2.1 Maximum Temperature Difference vs Temperature Increasing Rate..........61
    6.2.2 Fuel Channel set at 1073 K with Different Heat up Methods for Air Channel 75
  6.3 Conclusion....................................................................................................................78
7 Thermal Stress..................................................................................................................79
  7.1 Introduction...................................................................................................................79
  7.2 Results/Discussion..........................................................................................................79
  7.3 Thermal Stress Conclusion..........................................................................................89
8 Conclusion..........................................................................................................................90
9 Recommendation and Future Work..................................................................................92
References ................................................................................................................................. 94

Appendices ........................................................................................................................................ 99

10 Appendix A - Average Commuting times across Canada .......................................................... 99

11 Appendix B - Reynolds Number Calculation ............................................................................ 100

12 Appendix C - Maximum Temperature Gradients along Fuel Channel Symmetry for Single Channel Studies ........................................................................................................................................ 101

13 Appendix D - Maximum Temperature Gradients for Dual Channel Heat Up Method along Air Channel Symmetry ................................................................................................................................. 103
LIST OF TABLES

Table 1: Comparison of the heat-up time and the effective maximum-temperature-gradient under various heating configurations with a 10kW burner [27] ..................................................15

Table 2: Dimensions of SOFC channel used for model .............................................................................................................................33

Table 3: Heat up times for single channel and 10 cell stack .........................................................................................................................34

Table 4: Component material properties ..................................................................................................................................................35

Table 5: Material properties for air and fuel channels ............................................................................................................................36

Table 6: Meshing characteristics used for Model ....................................................................................................................................37

Table 7: Mesh refinement results .............................................................................................................................................................38

Table 8: Material properties used for validation [28] .................................................................................................................................39

Table 9: Heat up times for single channel studies less than 20 minutes (1200s) ....50

Table 10: Ranking of heat up methods by highest to lowest temperature gradients for single channel heat up methods at 20 m/s inlet velocity ..................................................................................57

Table 11: Steady state temperature gradients for single channel heat up methods ranked highest to lowest .................................................................................................................................59

Table 12: Comparison of heat up times between single channel and double channel for inlet velocity of 20 m/s ...........................................................................................................................................63

Table 13: Summary of heat up times for dual channel studies under 500 seconds ......64

Table 14: Comparison of temperature gradients for dual channel studies along air and fuel channel with inlet velocity of 20 m/s ........................................................................................................71

Table 15: Comparison of steady state temperature gradients and maximum temperature gradients with heat up times for dual channel studies ..............................................................................75

Table 16: List of average commuting times across Canada ................................................................................................................................99

Table 17: Constant values used for Reynolds number calculations .........................................................................................................100

Table 18: Reynolds number for air inlet velocities .................................................................................................................................100
LIST OF FIGURES

Figure 1: Cross Flow SOFC cell repeat unit [36] ................................................................. 2
Figure 2: 1D SOFC channel layout ................................................................................. 2
Figure 3: I-E characteristics and power density at 600°C under different start-up rates[17] .................................................................................................................. 8
Figure 4: Temperature distribution on the active cell area for different flow arrangements [4] .................................................................................................................... 10
Figure 5: Temperature contour over the active PEN area for co-flow arrangement [K] [21] ......................................................................................................................... 11
Figure 6: Stress distribution along active PEN area after 1000-hour use [24] ............. 13
Figure 7: Net heating energy comparison between furnace and hot air heating method [26] ...................................................................................................................... 15
Figure 8: Design map showing effect of changing heating rate and velocity on heat up times [28] .................................................................................................................. 17
Figure 9: Comprehensive comparison of the start-up time and the effective maximum absolute temperature-gradient for the case using hydrogen for the effect of the fixed temperature difference mechanism [29] ............................................................................. 18
Figure 10: Change of average temperature over time for the DIR-SOFC [1]............... 20
Figure 11: Probability of failure of PEN during the cell operation for IR-SOFC [1]..... 21
Figure 12: Maximum principle stress of investigated cases of different interconnect designs [31] ............................................................................................................... 22
Figure 13: Maximum principle stress and response time for the heat-up simulation at different temperature differences [31] ............................................................................. 23
Figure 14: Geometry of unit cell modeled for current research project .................. 30
Figure 15: Close up of geometry modeled for current research project .................. 31
Figure 16: Close up of geometry modeled including labels of SOFC components ...... 32
Figure 17: Close up of meshing used for this model .................................................... 37
Figure 18: Geometry used for validation study [28] .................................................... 40
Figure 19: Heat up times for current model compared with two other models in literature used for validation ..........................................................41

Figure 20: Areas of interest within SOFC where temperature gradients were measured for single channel and dual channel studies ..........................................................42

Figure 21: Fuel channel symmetry maximum temperature gradients for single channel heat up with inlet temperature set to 873K for different inlet velocities .................................44

Figure 22: Air channel symmetry maximum temperature gradients for single channel heat up with inlet temperature set to 873K for different inlet velocities .................................45

Figure 23: Fuel channel symmetry maximum temperature gradients for single channel heat up with inlet temperature set to 1073K for different inlet velocities .................................46

Figure 24: Air channel symmetry maximum temperature gradients for single channel heat up with inlet temperature set to 1073K for different inlet velocities .................................47

Figure 25: Heat up times for single channel studies at different inlet velocities .................49

Figure 26: Temperature profile along air channel for single channel studies ..................51

Figure 27: Maximum temperature gradients along air channel symmetry plane for single channel heat up methods with inlet velocity of 15 m/s ..........................................................52

Figure 28: Maximum temperature gradients along air channel symmetry plane for single channel heat up methods at inlet velocity of 20 m/s ..........................................................53

Figure 29: Maximum temperature gradients along air channel symmetry plane for single channel heat up methods at inlet velocity of 25 m/s ..........................................................54

Figure 30: Maximum temperature gradients along fuel channel symmetry for single channel heat up methods at inlet velocity of 15 m/s ..........................................................55

Figure 31: Temperature profile along fuel channel for single channel studies ...............56

Figure 32: Maximum temperature gradients over time for single channel studies with inlet velocity of 15 m/s ...............................................................................................58

Figure 33: Heat up times for all dual channel studies at different inlet velocities ..........62

Figure 34: Temperature profile along fuel channel for two dual channel maximum temperature difference studies ...............................................................................................65

Figure 35: Maximum temperature gradients for 100 K temperature heat up method for both single and dual channel studies with an inlet velocity of 20 m/s .................................66
Figure 36: Air channel symmetry maximum temperature gradients for dual channel heat up methods with inlet velocity of 15 m/s .................................................................67

Figure 37: Air channel symmetry maximum temperature gradients for dual channel heat up methods with inlet velocity of 20 m/s ..................................................................68

Figure 38: Air channel symmetry maximum temperature gradients for dual channel heat up methods with inlet velocity of 25 m/s ..................................................................69

Figure 39: Fuel channel symmetry maximum temperature gradients for dual channel heat up methods with inlet velocity of 15 m/s ..........................................................70

Figure 40: Fuel channel symmetry maximum temperature gradients for dual channel studies with heat up times under 20 minutes with inlet velocity of 20 m/s ....................72

Figure 41: Air channel symmetry temperature gradients for dual channel studies with heat up times under 20 minutes with inlet velocity of 20 m/s ............................................73

Figure 42: Maximum temperature gradients over time for dual channel studies............74

Figure 43: Dual channel heat up method with fuel channel set to 1073 K and air channel having set temperature difference of 100 K...............................................................76

Figure 44: Maximum temperature gradients over time with fuel channel inlet set at 1073 K with air channel set at two different heat up methods .........................................................77

Figure 45: Thermal stress for dual channel studies along anode when the temperature gradients of the maximum temperature difference methods are highest ......................80

Figure 46: Thermal stress for dual channel studies along cathode when the temperature gradients of the maximum temperature difference methods are highest ......................81

Figure 47: Thermal stress along anode for single channel heat up methods at 2 s without residual stress ......................................................................................................82

Figure 48: Thermal stress along cathode for single channel heat up methods at 2 s without residual stress ......................................................................................................83

Figure 49: Thermal stress along anode for dual channel heat up methods at 2 s without residual stress ......................................................................................................84

Figure 50: Thermal stress along cathode for dual channel heat up method at 2 s without residual stress ......................................................................................................85

Figure 51: Thermal stress along anode for single channel heat up methods at 10 s without residual stress ......................................................................................................86
Figure 52: Thermal stress along cathode for single channel heat up method at 10 s without residual stress ................................................................. 87

Figure 53: Thermal stress along anode for dual channel heat up methods at 10 s without residual stress ........................................................................ 88

Figure 54: Thermal stress along cathode for dual channel heat up methods at 10 s without residual stress ................................................................. 89

Figure 55: Maximum temperature gradients along fuel channel symmetry for single channel heat up methods at inlet velocity of 20 m/s ................................................................. 101

Figure 56: Maximum temperature gradients along fuel channel symmetry for single channel heat up methods at inlet velocity of 25 m/s ................................................................. 102

Figure 57: Air channel symmetry maximum temperature gradients for dual channel heat up methods with inlet velocity of 20 m/s ................................................................. 103

Figure 58: Dual Channel Fuel Channel Symmetry Temperature Gradients with inlet velocity of 25 m/s ........................................................................ 104
## NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_p$</td>
<td>Specific heat</td>
</tr>
<tr>
<td>$E$</td>
<td>Young's modulus</td>
</tr>
<tr>
<td>$F$</td>
<td>Failure</td>
</tr>
<tr>
<td>$K_{eff}$</td>
<td>Thermal conductivity of material</td>
</tr>
<tr>
<td>$K$</td>
<td>Thermal conductivity for SOFC components</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
</tr>
<tr>
<td>$T_{ref}$</td>
<td>Reference temperature</td>
</tr>
<tr>
<td>$T_{inlet}$</td>
<td>Inlet temperature</td>
</tr>
<tr>
<td>$T_{init}$</td>
<td>Initial temperature</td>
</tr>
<tr>
<td>$T_{inc}$</td>
<td>Ramp rate per second</td>
</tr>
<tr>
<td>$T_{in}$</td>
<td>Minimum temperature throughout SOFC</td>
</tr>
<tr>
<td>$T_{ramp}$</td>
<td>Input temperature for ramp studies</td>
</tr>
<tr>
<td>$T_{set}$</td>
<td>Set temperature difference</td>
</tr>
<tr>
<td>$U$</td>
<td>Inlet Velocity</td>
</tr>
<tr>
<td>$V_0$</td>
<td>Reference volume</td>
</tr>
</tbody>
</table>
GREEK SYMBOLS

\( \sigma_{th} \)  Thermal stress

\( \alpha \)  Thermal expansion coefficient

\( \sigma \)  Applied stress

\( \sigma_0 \)  Characteristic strength

\( \rho \)  Density of material

\( \varphi \)  Porosity

\( \varepsilon \)  Total strain

\( \varepsilon_{th} \)  Thermal strain

\( \varepsilon_{el} \)  Elastic Strain

\( \gamma \)  Shear Strain
1 Introduction

Solid oxide fuel cells (SOFCs) are electrochemical conversion devices that are mainly used for stationary power and heat generation [1]. Because of their high operating temperatures (~700-1000 °C), SOFCs may be used in combined heat and power (CHP) systems. Since SOFCs operate at high temperatures they can use a wider range of fuels compared to other low to mid temperature fuel cells. In addition to hydrogen, natural gas and other hydrocarbons can be used as a fuel source in SOFCs [2]. This is due to the ability of using internal reforming when operating at high temperatures. Another benefit of SOFCs over other types of fuel cells are their high efficiency. Due to the fact that they can provide waste heat for co-generation applications, efficiencies of over 60 % can be achieved [3]. With the high efficiencies as well as the different fuel types that can be used, SOFCs are an appealing option for power generation as well as automotive applications.

At the fundamental level, SOFCs are comprised of four components: an anode, cathode, electrolyte, and interconnect layer. For example, Figure 1 shows an exploded view of a 5-channel cross-flow repeat unit. In order to increase the power output, cells are connected in series to form stacks. Each stack can have a range of cells, depending on the power needs of the system.
When modelling a fuel cell, the operating conditions along one of the flow channels can be used to represent the operation of the entire cell and/or stack. A single channel of an SOFC cell is seen below in Figure 2. The flow channel that has air moving through it is also called an air channel, and the flow channel with the hydrogen moving through it is the fuel channel.
The main reactions that occur in the SOFC are similar to other types of fuel cells, where hydrogen reacts with oxide ions in the anode to form water and release electrons. At the cathode, the electrons react with the oxygen to produce the oxide ions which transport through the electrolyte to the anode. The reactions at the anode and cathode as well as the overall cell reaction can be written as:

1. Anode: $H_2 + O^{2-} \rightarrow H_2O + 2e^-$

2. Cathode: $\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$

3. Overall: $\frac{1}{2}O_2 + H_2 \rightarrow H_2O + Waste\ Heat + Electrical\ Energy$

The two main types of SOFCs are planar and tubular. Tubular designs allow for better resistance to thermal stresses, and there is no need for gas-tight cell sealing [3]. However, the material costs are quite high, and they have a low power density which make them unsuitable for large scale power applications. Planar designs allow for higher power densities, lower fabrication cost and ease in gas flow management [3]. Planar designs are also the most common type of SOFC on the market and highly researched today.

Currently the market for fuel cell vehicles is small, with Proton Exchange Membrane (PEM) fuel cells being the only type of fuel cell being used. This is mainly due to the lower operating temperature which allows for quicker start up times, and less issues that come with a high temperature fuel cell. But PEM fuel cells are limited to pure hydrogen as fuel [3]. This inhibits the breakthrough of PEM fuel cell vehicles until a hydrogen infrastructure can be established. This is where the market for SOFC vehicles
can be established. Because of their ability to use hydrocarbons as fuel, no new fueling infrastructure would need to be developed for fuel cell vehicles operating with SOFCs. However, there are currently limitations on implementing them for automotive purposes. The main issue in using SOFCs for automotive applications is their high operating temperature (~700 °C) [4]. When using a vehicle, the expectation is that the car will start instantaneously no matter what is powering the vehicle. A 2016 Statistic Canada study found that the average commute was 24.1 minutes when Canadians drove to work [33]. Table 16 in Appendix A, shows the average commute for different cities throughout Canada. Fuel cells cannot start instantly, and specifically with SOFCs, they require an even longer time to start up due to the nature of the ceramic materials used and the high operating temperature. To be competitive, the heat up times for vehicles using SOFCs would need at a minimum be close to the average commute time if they were paired with a battery. The main limitation of a rapid startup of a SOFC is the thermal stresses that can develop. Depending on the configuration, materials, and size of the SOFC, there is a limit to how rapidly the cell can start up without failing because of the thermal stresses that can develop from the high temperature gradients that may exist during start up.

2 Objectives

The purpose of this research is to investigate how rapidly an SOFC can be heated up to its operating temperature without failing. The aim is to quantify the temperature gradients that are developed during the heat up process of a SOFC. Then, with the temperature gradients measured, what are the corresponding thermal stresses that are developed? Finally, incorporating the temperature gradients, thermal stress, and location of these, is there an optimal heat up strategy to lower heat up times of SOFCs? This will be done by developing a model to simulate the heat-up time using COMSOL Multiphysics, calculating the temperature gradients that develop and then calculate the thermal stress. The model will look at the time it takes for a SOFC to reach an operating temperature of
600 °C (the temperature at which electrochemical reactions begin to take place). The model will simulate both single channel (air channel) heat up methods as well as dual channel (both air and fuel) heat up methods. Included in the model will be a thermal stress analysis component, to investigate the thermal stresses that occur during each heat up process of the SOFC. Different heat-up strategies and techniques will be investigated including: introducing the air and fuel channels with gases at operating temperature, limiting the maximum temperature difference throughout the cell to set amounts, and ramping up the inlet temperatures by a set amount per second, to investigate their effect on the heat-up times without causing the SOFC to fail due to the high thermal stress and if this is feasible for automotive applications.

3 Literature Review

As stated previously, there is minimal research being done on using a planar SOFC as the power source for automotive applications, either alone or paired with an electric battery. The studies that are being done do not focus on the time it takes for a vehicle using an SOFC to start running. Limited research does quantify the start-up times, but they mainly focus on SOFCs for auxiliary power units (APUs), or tubular SOFCs.

There are different ways in which stresses occur and are created in SOFCs. In individual cells, there are residual stresses that occur during the manufacturing process. This is mainly from the sintering phase in the manufacturing stage of the SOFC. The residual stresses are created from the mismatch of the thermal expansion coefficients (TEC) during this process of the different materials in the SOFC [5]. As well, high residual stresses are formed when there is a difference between the cell temperature and the zero-stress temperature (ZST). The ZST is the temperature at which the seals are added, or the sintering process of the SOFC during manufacturing [6]. The ZST is usually assumed to be around 1200-1300 K, depending on the study that is being done and when
the final joining process of the fuel cell components occurs. When the fuel cell component temperature does not equal the ZST, residual stresses are formed due to deformation of each component in the SOFC. This means that at room temperature, high residual stresses are expected to occur in the fuel cell. However, due the different TEC, the electrolyte and cathode have shown to have more favorable compressive residual stress, while the anode is the component that experiences unfavourable tensile residual stress at room temperature [7]. The values in literature tend to be in the range of 500-800 MPa in the electrolyte, 20-60 MPa in the cathode for the compressive stresses, and 45-90 MPa in the anode for the tensile stress [7].

Another cause of stress in SOFCs are from different temperature gradients throughout the cell. Temperature gradients can occur during the heat-up/start-up of the SOFC, as well during steady state and transient operation of the fuel cell. The thermal stresses in the fuel cell are calculated using the temperature of the fuel cell, the ZST, as well as the thermal expansion coefficient [8]. The following equation is how the thermal stress, $\sigma_{th}$, is calculated:

$$
\sigma_{th} = \alpha E (T - T_{ref})
$$

Where $\alpha$ is the TEC, $E$ is Young’s Modulus, $T$ is the temperature, and $T_{ref}$ is the zero-stress temperature. Thermal stress is also significantly affected by the mismatch of TECs throughout the fuel cell [9]. These thermal stresses are what can contribute to the failure of an SOFC due to cracking or fuel leakage during operation if not correctly managed. It is also the main reason SOFCs are limited in how quickly they can be heated up.

When looking at an SOFC stack, the stresses that occur are the same as in each individual cell expect for one additional source of stress. During the assembly of the stack, a compressive load has to be applied in order to correctly seal all of the cells together [10]. This load can range in value, but adds a source of stress on the stack that
can contribute to failure during operation [11]. Each type of stress that occurs in a SOFC during either the manufacturing, assembly, or operation contributes to the potential failure at some point during the fuel cells life [5].

3.1 Start-up Times for APUs

The current research that has been done for SOFCs in automotive applications is mainly in APUs. Delphi and BMW have researched APUs using SOFC in their vehicles as a way to conserve fuel [14]. The model looked at how long it would take for the system to reach steady state operation. It was calculated that the APU could reach steady state operation in about 100 seconds. However, the downside of the model is that it does not account for thermal stresses which makes the start-up time purely theoretical. Petruzzi et al. use a similar model but added in temperature gradients to account for thermal stresses [15]. The results indicate a start-up time of almost 15 minutes, which shows the importance of calculating thermal stress in any start-up time model.

3.2 Start-up Times for Tubular SOFCs

The benefit of using tubular SOFCs is the fact that they do not need gas seals, which makes them less likely to fail due to thermal stress [16]. One such study [17] looked at the effect of a honeycomb supported tubular SOFC under rapid start-up operation. The results of the study showed that the cell responded well to a rapid start-up of 100 °C/min as seen in Figure 3:
As seen from Figure 3, a rapid start up results in a slight decrease in the power density and an increase in the voltage drop. This suggests that no thermal stress or failure was found in the cell when started up with a heating rate of 100 °C/min [17].

Another model looked at a numerical analysis of the start-up of a tubular SOFC, looking at the temperature, cell output voltage, and the state variables (pressure, temperature, and species concentration) [18]. The results from this study showed an average start-up time of 2.5 hours, with a maximum heat up rate of 30 °C/min. The problem with this study, is it did not investigate a rapid start-up, so it cannot be certain if this is the fastest the cell could be started. One result from Barzi et al [18], was the fact that the highest temperature gradients occurred right at the beginning of the start-up.
phase. This shows that if the cell can withstand the initial increase in thermal stress, the probability of the cell failing after that point will decrease.

A study by Yamaguchi et al [17], was also done on a micro-tubular SOFC to look at the effects of a rapid start-up. The results showed that the cell could withstand rapid thermal cycling and could achieve a start-up time of under one minute. The problem with this study is that it is for a micro-SOFC with power output of approximately 350 mW. For an automotive application, this is not suitable, even for an APU application. As well, tubular SOFCs tend to have lower power densities and are more expensive to manufacture compared to planar SOFCs [17] [18], which is why planar SOFCs are considered more promising type of SOFC for automotive applications.

### 3.3 Current SOFC Models

There are a variety of models developed in the literature, with varying complexity, for anode supported planar SOFCs. This next section highlights the models that have been developed, which will show the gap in research in regard to a model being developed to analyze the start-up times of an SOFC for automotive applications.

The first type of model that is developed for SOFCs focuses on performance characteristics of the fuel cell. One such study uses a 2D and 3D simulation that considered mass, charge, and heat balances along the flow channel to show temperature gradients throughout the cell [19]. Using a unit cell as the geometry of the model, the results show that a co-flow cell arrangement provides less temperature increases than that of a counter-flow arrangement. This is confirmed by another model developed by K.P. Recknagel et al. who develop a simulation tool for modeling a planar SOFC stack [4]. Using the software program STAR-CD, co-, counter-, and cross-flow stack arrangements are simulated to look at the different temperature gradients. As shown in Figure 4 [4], it can be seen that the co-flow arrangement provides the lowest temperature gradients:
Both models are in agreement about the orientation of the fuel cell to best minimize temperature gradients and it is mentioned that it could lead to lower stresses in the cell [19]. However, the thermal stresses are not quantified in the models and start up times are not determined with the models.

Other models [20] [21] are also in agreement with the two above and focus their model on different parameters. For example, one model uses FORTRAN to compare temperature increases in anode supported vs electrolyte supported cells [20]. It was found that an anode supported SOFC produced less rise in temperature than an electrolyte supported SOFC, however no explanation into the reason for this was given. The geometry that was modeled was a unit cell, and it was assumed the results would be similar for a stack design [20]. Another 3D model using FLUENT investigated the performance characteristics of a 20 kW SOFC design focusing on pressure, mole fraction, and temperature gradients [21]. This model confirms the assumption that temperature increase is still low for a stack design as compared to a cell design for a co-flow arrangement as seen in Figure 5 [21].

Figure 4: Temperature distribution on the active cell area for different flow arrangements [4]
One final model developed by Choudhary and Sanjay, focuses on the performance of an SOFC that uses internal reforming [22]. The model looks at the thermodynamic, electrochemical process, and how the flow configuration affects the temperature gradients [22]. Where the previous models just modeled the SOFC using hydrogen, this model takes advantage of one of the benefits of SOFCs - internal reforming. As stated by M. Iwata et al., the lower temperature gradient can result in lower thermal stresses, but this model like the others do not account for the thermal stresses in the models [19]. The models also provide evidence that co-flow arrangements would be best for automotive applications due to the lower temperature gradients [19], [22].

Another set of models considered the temperature profiles of the fuel cell during operation and calculated the thermal stresses that occurred from the varying temperature profiles. The models vary in complexity and the aim of the desired outcome in results. One such model by Yakabe et al. focused only on steady state operation, using the simulated temperature distributions to calculated the stress distributions in the electrolyte and interconnect [23]. Using a single unit cell for a planar electrolyte supported cell for the geometry, Yakabe’s et al. model provided results on where the highest stress
concentrations would be during steady state operation. It was found that the highest stress concentrations occurred near the fuel inlet, and the co-flow arrangement would in fact lower the stress concentrations [23]. A similar model goes one step further and calculates the probability of failure using the Weibull statistic [20]. The model looks at varying anode and electrolyte thickness to see how the thermal stress varies. The results showed that the anode is the critical section in steady state operation [7], but like Zhang's et al. model investigating stress concentration in the interconnect, does not account for the start-up phase.

Other models focus on the long term performance of a SOFC in regards to stress [24] [25]. Both studies use their models to cycle a SOFC over more than 1000 hours to investigate the long-term durability of the stacks. The model by Clague et al. included residual stress which had a significant effect on the stress magnitude in the fuel cell at operating conditions [24]. The model also investigated a change in electrical load after long term use of the SOFC to see if the stress distribution was different. Figure 6 [24] shows that even after long term use, the stress concentration is highest at the fuel inlet which is in agreement with the previously mentioned thermal stress models by Zhang et al. [7] and Yakabe et al. [23].
Figure 6: Stress distribution along active PEN area after 1000-hour use [24]

As it can be seen from Figure 6, the highest stress distribution is at the fuel inlet of the SOFC stack due to the higher temperature gradients occurring there. These models however still do not account for the start-up process, instead focusing on long term use of the fuel cell.

An additional set of models used residual stress on top of thermal stress, but focused on the sealing properties of the SOFC, to see whether the type of sealing design contributed to the failure of the cells from thermal stress. One study by Lin et al. looked at the effect of sealing design for a SOFC stack and how the thermal stress changed [10]. The results concluded that at room temperature, the effect of the sealants lowered the calculated thermal stress, but during operation the stack would experience higher thermal stress. The conclusion showed that it would be important to account for the type of
sealant in a stack design, but does not specify if it would be the same for start-up procedures [10]. Another study by Jiang and Chen looked at a specific sealing design called the bonded compliant seal. This design accommodates the extent of deformation between components during operation, allowing for thermal deformation to be partially absorbed [6]. The results from the study were consistent of that in the literature, showing higher stress concentrations at the fuel inlets, as well as the edge of where the sealant was applied. Another conclusion from the study was the fact that the temperature gradients contributed to the thermal stress the same amount when compared to using a bonded glass-ceramic seal [6].

3.4 Models Focusing on Heat-up and Start-up

The previously mentioned models encompass the bulk of research that is being done on steady state operation, with models focusing on thermal stress as well as performance characteristics. The next area of research where models have been made focuses on the heat up and start-up of the SOFC. The heat up being the initial warm up of the SOFC until reactions can take place on the anode side, and the start-up being from when the first reaction can take place to steady state operation. Some models look at both the heat-up and start-up of the SOFC while others look at one of the two.

Two of the most common heat-up strategies for a SOFC are by a furnace or by hot air through either the gas or air channels. Most commonly, the air channels are used to provide warm air until the fuel cell is warmed up to the minimum operating temperature [26]. A third way, investigated by Ming-Hong Chen and Tsung Leo Jiang, is by dual channel heating, where exhaust gas from a methane burner and hot air is used to warm the fuel cell [27]. In this model, the single channel heat up method is compared to a co-flow and counter flow dual channel heat up method. The results showed that the heat-up time was drastically reduced when using the dual channel heat up strategy as seen in Table 1 [27]:

14
Also seen from Table 1, is that the counter-flow heat up time is lower than the co-flow and produces slightly higher maximum temperature gradients. The problem with this model is that it does not show if the temperature gradients formed using this heat-up strategy correspond to thermal stress below the failure limit. A model that compares furnace heating to the hot air heating method shows that furnace heating allows for quicker warm up time than hot air as shown in Figure 7 [26]:

<table>
<thead>
<tr>
<th></th>
<th>Co-flow</th>
<th>Counter-flow</th>
<th>Single-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>658</td>
<td>560</td>
<td>1439</td>
</tr>
<tr>
<td>Effective maximum-temperature-gradient (K cm⁻¹)</td>
<td>18.9(6 s)</td>
<td>22.6(end)</td>
<td>13.7(end)</td>
</tr>
</tbody>
</table>

Figure 7: Net heating energy comparison between furnace and hot air heating method [26]
The downside of this model is that it does not compare the dual heat up strategy to the furnace method to see if there is still the significant difference in heat up times. As well, for automotive applications using a furnace as the source for the heat up method could be problematic and difficult to achieve.

One other model by developed by Damm and Fedorov [28], looks only at the heat up time of an SOFC to develop a design map from a reduced order thermal model [28]. The model by Damm and Federov investigated the feasibility of using a simplified thermal model to find the heat up time in a typical anode supported SOFC. It was found by varying the inlet velocities ($U_{in}$) of the air channels as well as the rate of temperature rise per second (K/s) either increased or decreased the time to raise the fuel cell temperature from 25-625 °C. This allowed for a design map to be made which could accurately show the effect of changing the $K$ and $U_{in}$ values on temperature gradients and heating time as seen in Figure 8 [28]:
The map shows that increasing the inlet velocity of the air will lower heating time and temperature gradients whereas increasing the rate of inlet temperature rise produces higher and lower heating times and gradients depending on the inlet velocity.

For the start-up phase of the SOFC, the model developed by Chen and Jiang investigated three different start-up procedures to compare temperature gradients, and time to reach steady state operation [29]. The three start-up procedures were: have the inlet fuel at operation temperature, incorporate an anode-recycling mechanism, and the third was to fix the difference in temperature between the inlet-fuel temperature and the fuel cell minimum temperature. For the case of anode-recycling, it was found that the start-up times were around 20-45 minutes depending on the percentage that was recycled [29]. When comparing various fixed temperature differences with keeping the inlet
temperature at operating conditions, the time is lowered. Figure 9 shows three different temperature differences and compares them to the original [29].

![Bar Graph](image_url)

**Figure 9**: Comprehensive comparison of the start-up time and the effective maximum absolute temperature-gradient for the case using hydrogen for the effect of the fixed temperature difference mechanism [29]

From Figure 9, with a temperature difference of 250 K a start-up time of 188 seconds can be achieved. When looking at what provides the lowest temperature gradients, using 100 K as the temperature difference produces the lower gradients. When using methane as the as the fuel allows for lower temperature gradients overall, however it has quite a bit longer start-up time than hydrogen [29].

Generally, the models used to predict heat-up and start-up times focus on the temperature profile and performance of the SOFC during these stages. Thermal stresses are not accounted for in these models which make it difficult to see if the start-up and heat-up times are achievable, or just applicable when excluding the material and thermal stress side of the SOFC models [26].
3.5 Models Incorporating Start up and Thermal Stress

The final group of models combines thermal stress analysis with some type of start-up or heat-up model to show not only start-up times, but the stresses that will occur during these stages. The models vary in complexity, with some models only mentioning the start-up portion of the SOFC in operation, with the main focus being steady state operation. Others go into more detail comparing performance as well as thermal stresses that occur in different configurations of the SOFC, as well as different fuels. Each model mentioned in this section provides important details about SOFCs during the start-up stage, but also leaves room for more research to be done to better understand the start-up times of SOFCs.

The first model by Choudhary and Sanjay provides a computational analysis of an internal reforming SOFC, focusing on transient operation as well as thermal stress [30]. For the transient part of the model, the start-up behavior is investigated, however the focus is on the transient response to a change in load during operation. The results from the study show that a SOFC with co-flow arrangement provides lower thermal stresses than that of a counter-flow design [30], which is in agreement with previous studies. It does mention that counter flow arrangement provides a higher power and average current density than co-flow arrangement but at a lower efficiency. It goes on to mention that the co-flow arrangement has a shorter response time of 2875 s to reach steady state. The model does not investigate ways to lower that time, or specify what method was used for the heat-up and start-up phase.

A different model by Colpan et al. [1] also models an internal reforming SOFC but focuses solely on the heat-up and start-up model. This model provides a detailed study on the heat-up and start-up periods for both a co- and counter- flow arrangement [1]. The study models a unit electrolyte supported SOFC with an operating temperature of 900 °C. However, for the heat up of the SOFC, the model only investigates the method that keeps the temperature difference at 100 °C during heat-up. Comparing average solid
temperature of the SOFC during start-up in Figure 10 [1] shows that co-flow exhibits a slightly lower temperature than a counter flow arrangement.

![Graph showing temperature change over time for DIR-SOFC](image)

*Figure 10: Change of average temperature over time for the DIR-SOFC [1]*

On top of investigating the temperature differences during the start-up phase of the SOFC, the probability of failure for each case is also determined. After determining the first principle stresses during the heat up and start-up phase, the probability of failure is calculated. Figure 11 [1] shows that the probability of failure is lower for a co-flow arrangement.
This model goes into a bit more detail than previous models when looking at heat up and start-up times, however it still leaves room for more research to be done. Specific start up times are not calculated; the model focuses on thermal stress and probability of failure. As well, different start-up methods are not investigated to see if other ways provide quicker start-up times.

The model developed by Lin et al. [9] models a planar SOFC stack to look at the thermal stress analysis that occurs during different stages of operating the SOFC, including the start-up phase [9]. On top of using a stack model for the simulation, the study incorporates a glass-ceramic sealant into the model to provide a more accurate thermal stress calculation. The temperature profiles were imported into ABAQUS to calculate the thermal stress at specific times throughout the start-up process and at steady state [9]. Results showed that the highest thermal stresses occurred during the initial time period of the start-up and got lower as the fuel cell reached steady state. It also found that TEC mismatch affected the thermal stress distribution more than temperature gradients did. However, there was no mention of calculated start up times.
in the model, with the focus being more on the distribution of stresses during start-up [9]. The model confirmed the observations in previous studies that thermal stress would be highest during the beginning of the start-up phase but did not specify if this was the case for different start-up techniques.

Selimovic et al. investigated the start-up times and thermal stresses for a planar SOFC using two different types of material for the interconnect design [31]. The model looked at metallic and ceramic interconnects, and the effect they had on start-up times as well as with different fuel types. Calculating the maximum principal stresses for each scenario shows that the ceramic interconnect causes the highest thermal stress no matter what the fuel type is as seen in Figure 12 [31].

As well, the start-up times and maximum principal stresses are compared with various temperature differences during the heat-up stage. It was found that the heat up times changed at the same rate for metallic and ceramic interconnect, but the thermal stresses increased more in the ceramic interconnect as shown in Figure 13 [31]:

![Figure 12: Maximum principle stress of investigated cases of different interconnect designs [31]](image-url)
The study concludes that the heat up time for both types of designs is the same at about 2.5 hours with a ΔT of 100 K. As well, the ceramic cell can be started up in about 30 min with hydrogen as the fuel, but does not mention the start-up time for the metallic interconnect design [31]. Like the model by Colpan et al. [1], only one type of warm up stage is investigated and only one start up method is looked at as well. The model by Selimovic et al. provides more detail on the times that can be anticipated it takes to start up a SOFC, but more research can be done in this area to see if the times can be lowered.

The models presented above illustrate the gap in research in investigating start up times of SOFCs for automotive applications. Being able to quantify the start-up times of a SOFC used for automotive applications is a very important step in investigating the feasibility of using them for automotive purposes. If the start-up times are too high, the feasibility of using SOFCs is reduced. That is why there is a need for a model that can
specify the time needed to heat up the fuel cell until electrochemical reactions can take place, then the time needed to start the SOFC. The calculation of thermal stresses can be used to assess if the heat up times are feasible. For this research project, a model using the software package COMSOL was developed with the aim to quantify start-up times of SOFCs for an automotive application, considering the thermal stresses that would be found during this stage of operation.

4 Current Model Overview

For this research, COMSOL Multiphysics version 5.3a was used to calculate the temperature gradients and heat up time of a single channel of a SOFC as well as the thermal stresses that are developed throughout the SOFC during the heat-up process. The next few sections will discuss how the model was built, the geometry used for the study, material properties, and the equations used to solve the heat transfer and thermal stresses present during SOFC heat-up.

4.1 Modeling Principles Used

The benefit of using COMSOL is that multiple physics can be solved at once in one model, allowing for a wide range of results to be calculated. In this model, heat transfer, laminar flow, and solid mechanics physics are solved for using COMSOL. The first study combines the laminar flow and heat transfer physics to calculate the temperature gradients and heat up time. When calculating the thermal stress, the temperature profile from selected time steps are used to calculate the thermal stress at that moment in time.

4.1.1 Laminar Flow

As the current research is looking at how long it takes a SOFC to heat up to a temperature that allows the SOFC to start-up, it is assumed that no chemical reactions take place during the heat up of the cell. To model the fluid flow within the air and gas channels of
the SOFC, COMSOL uses the Navier-Stokes equation (Eqn 5), to represent the
conservation of momentum along with the continuity equation (Eqn 6) to represent the
conservation of mass. Both are solved together to model the fluid flow in the air and gas
channels.

\[
\rho \left[ \frac{\partial u}{\partial t} + u \cdot \nabla u \right] = -\nabla \rho + \nabla \mu \nabla u + \nabla \cdot (\nabla u)^T
\]

(5)

\[
\frac{\partial p}{\partial t} + \nabla \cdot (\rho u) = 0
\]

(6)

To simplify the calculations, a few assumptions were made. First, the flow of gas within
the air and fuel channels is expected to be laminar, as the Reynolds number when a
maximum velocity of 25 m/s is used is calculated to be 729. This Reynolds number is
less than the critical value for turbulent flow. Table 18 in Appendix B shows the Reynolds
number for the rest of the air inlet velocities used. Another assumption that was made for
the model was it would be incompressible flow. For gases, this occurs when the Mach
number is small. Since the air and fuel channel velocities are only 15-25 m/s assuming
incompressible flow is reasonable.

At the inlet of the channel(s), depending on the study, the inlet conditions were set for the
normal inflow velocity, and the outlet(s) were set to ensure no pressure drop in the
channel.

4.1.2 Heat Transfer

For the heat transfer portion of the model, the heat transfer physics was used. Heat
transfer modelling was broken down into heat transfer in fluids for the air and gas
channels and heat transfer in solids for the PEN and interconnect. Radiation was not
considered in this model as it was found that it had a negligible effect on the electrode
and electrolyte layers of the SOFC [32]. For the porous anode and cathode there was also heat transfer in porous media included in the heat transfer in solids section. For heat transfer in solids, it is due to conduction, and is used for both the solids and porous media materials.

\[
\frac{\partial}{\partial t}[(\rho C_p)T] = -\nabla \cdot (-k_{eff} \nabla T)
\]

Heat transfer via conduction takes into account the density of the material \( \rho \), specific heat \( C_p \), and the effective thermal conductivity of the material, \( k_{eff} \). COMSOL includes heat transfer through porous media by considering both the thermal conductivity of the fluid and solid portions of the material. For completely solid material, the \( k_{eff} \) is the same as the thermal conductivity of just the solid.

\[
k_{eff} = \phi k_f + (1 - \phi)k_s
\]

where \( k_{eff} \) is the effective thermal conductivity, \( \phi \) is the porosity, \( k_f \) is the thermal conductivity of the fluid, and \( k_s \) is the thermal conductivity of the solid. For the heat transfer for the air and gas channels, the velocity of the gases within the air and fuel channels are coupled with the heat transfer in fluid component of the heat transfer physics. The equation used considers the gases density, specific heat capacity, thermal conductivity as well as the velocity of the gases for the convective heat transfer.

\[
(\rho C_p)_f \frac{\partial T_f}{\partial t} = -\nabla \cdot (-k_f \nabla T_f) - (\rho C_p)_f u \cdot \nabla T_f
\]

For the inlet conditions for the heat transfer physics, the only constraint on temperature is the set inlet parameter. This sets how quickly and at what rate the temperature at the
inlet of the channel(s) increases. The rest of the physics is coupled with the laminar flow physics so that they both can be solved simultaneously during the study.

4.1.3 Custom Equations for Inlet Conditions and Stop Conditions Used in Model

To model the different heat up methods, different expressions needed to be entered correctly in COMSOL to depict the heat up methods being studied. For the ramp rate heat up methods, the following equation was used for the inlet temperature ramp up rate:

$$T_{inlet} = T_{init} + (T_{inc} \times rm1(t \left[ \frac{1}{s} \right]))$$

where $T_{init}$ is the initial temperature, set to 298 K, $T_{inc}$ is the ramp rate per second that is being studied, and $rm1$ is a custom COMSOL ramp function that increases in value every second. This allows for an accurate temperature input for the ramp rate studies.

For the set temperature difference studies, the following equations are used:

$$T_{in} = minop1(T)$$

$$T_{ramp} = T_{in} + T_{set}$$

where $T_{in}$ calculates the minimum temperature throughout the cell during the study. The $Minop1(T)$ function calculates what the minimum temperature is throughout the whole cell at every time step during the study. $T_{ramp}$ is the input temperature into the model, with $T_{set}$ being the set temperature difference parameter being studied.
4.1.4 Thermal Stress

For the thermal stress component of the model, the Structural Mechanics Module in COMSOL was used. This portion of the model incorporated the temperature profile calculated using the laminar flow and heat transfer modules to calculate the thermal stress throughout the SOFC during the heat up process. The main thermal strain equation used by COMSOL incorporates a reference temperature, TEC of the material, and the temperature of the material.

\[ \varepsilon_{th} = \alpha(T - T_{ref}) \]

where \( T \) is the temperature of the material, \( \alpha \) is the TEC of the material, and \( T_{ref} \) is the reference temperature. When the SOFC is heated, the components expand with temperature depending on the TEC of the material which cause thermal strains throughout the components. The overall strain throughout the SOFC are a summation of the thermal and elastic strain calculated below

\[ \varepsilon = \varepsilon_{el} + \varepsilon_{th} \]

where \( \varepsilon_{th} \) is the thermal strain calculated in the equation above, and \( \varepsilon_{el} \) is the elastic strain seen below:

\[ \varepsilon_{el} = (\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \gamma_{yz}, \gamma_{xz}, \gamma_{xy}) \]

where \( \varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \gamma_{yz}, \gamma_{xz}, \gamma_{xy} \) are the longitudinal and shear components for strain. As well, the stress-strain relationship is calculated as:
\[ \sigma = D \varepsilon + \sigma_o \]

where \( \sigma_o \) is the initial stress, which is the residual stress for this model. The elasticity matrix (D) for isotropic material is calculated by the following matrix:

\[
D = \frac{E}{(1 + \nu)(1 - 2\nu)} \begin{bmatrix}
1 - \nu & 0 & \nu & 0 & 0 & 0 \\
\nu & 1 - \nu & \nu & 0 & 0 & 0 \\
\nu & \nu & 1 - \nu & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1 - 2\nu}{2} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1 - 2\nu}{2} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1 - 2\nu}{2}
\end{bmatrix}
\]

where E is the Young’s modulus and \( \nu \) is the Poisson’s ratio of the material seen in Table 4. Together, these equations calculate the total stress that occurs throughout the cell while the heat up process is occurring.

For the reference temperature, two different scenarios were modeled and discussed later in the Thermal Stress Chapter (See Chapter 7). The first one calculated the stress when the reference temperature was set to 1073 K, which simulates when the SOFC is manufactured. The second scenario was when the residual stress was not calculated, and the reference temperature was set to room temperature, 298 K. For all the thermal stress scenarios, a fixed constraint was set at the bottom of the SOFC, with the rest of the cell free to deform. As done for the heat transfer and laminar flow component of the model, a symmetry plane was applied on half the cell.
4.2 Geometry

Depending on the power requirements, an SOFC stack can be different sizes, and have any number of cells in it. For this study only one channel of a single cell was modeled. This is because of the planar geometry of the SOFC, it can be assumed that each cell has the same flow properties and temperature distribution [27].

Figure 14 and Figure 15 show the single channel geometry that was used for this research.

Figure 14: Geometry of unit cell modeled for current research project
As well, Figure 16 shows a close up of the geometry as well as labelling the components that are in the SOFC. It can be seen from Figure 16 that the anode is larger than the cathode and electrolyte, which makes it an anode supported SOFC. Since the fuel cell channel is symmetrical, only half of the channel is modeled, with a symmetry plane being applied to the model at the centre of the channel (i.e., the right side of Figure 16 shown below). This allows for a reduction in how much of the geometry will be meshed. This in turn will allow for a reduction in computational time for the studies that are being conducted.
During this research, especially during the validation of the heat up time, it was noted that different geometries correspond to slightly different heat up times. This was especially the case with different anode widths and different heights of the fuel and air channels. For this model, because there is limited research done on heat up times for SOFCs in automotive applications, the chosen geometry of the cell was taken from a study by Chen and Jiang [27], as it allowed for easier validation of the model, and it was also used in a modeled developed by Hanjo [34]. This current research did not focus on how the change of geometry affects the heat up time. Table 2 shows the dimensions of the channel that is modeled for this research. All values are in millimeters and are the dimensions of the fuel cell that is shown in Figure 16.
To confirm that the heat up times also would be the same, a validation study was run using the single channel 1 K/s heat up method at three different inlet velocities: 15 m/s, 20 m/s, and 25 m/s. The results, as shown below in Table 3, confirm that the results using a single channel geometry versus a 10 cell stack have a similar heat up time.
Table 3: Heat up times for single channel and 10 cell stack

<table>
<thead>
<tr>
<th>Inlet Velocity</th>
<th>15 m/s</th>
<th>20 m/s</th>
<th>25 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>single channel heat up time (s)</td>
<td>792</td>
<td>726</td>
<td>706</td>
</tr>
<tr>
<td>10 cell stack heat up time (s)</td>
<td>766</td>
<td>752</td>
<td>730</td>
</tr>
<tr>
<td>% difference</td>
<td>3.30%</td>
<td>3.50%</td>
<td>3.30%</td>
</tr>
</tbody>
</table>

The difference in heat up times for the single channel vs stack is only about 3 %, which confirms that the assumption that each channel has similar characteristics in a stack is correct. Another benefit of using a single channel geometry for this research is the computational time required for a stack. A one cell study took 15 minutes to complete, while the same study using the stack geometry reached a computational time of over 2.5 hours because of the amount of meshing required.

4.3 Materials

For this model, the material properties were taken from two papers [27] [31], one that analyzed the thermal behavior in a planar SOFC and another that looked at the thermal stress throughout the SOFC during operation. The anode is made of Ni-YSZ, the electrolyte 8YSZ, and the cathode of LSM, which is what SOFCs are commonly made with. A benefit of COMSOL is the fact that material properties can be manually entered and edited for different simulations. As the materials for the SOFC were not in the COMSOL database, custom materials were made for each component and entered
manually. For the solid structure, Table 4 below summarizes the properties of each component.

Table 4: Component material properties

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Anode</th>
<th>Cathode</th>
<th>Electrolyte</th>
<th>Interconnect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity (W/(m*K)) [27]</td>
<td>5.84</td>
<td>1.86</td>
<td>2.16</td>
<td>20</td>
</tr>
<tr>
<td>Density (kg/m³) [27]</td>
<td>3030</td>
<td>3310</td>
<td>5163</td>
<td>8030</td>
</tr>
<tr>
<td>Heat Capacity (J/(kg*K)) [27]</td>
<td>595</td>
<td>573</td>
<td>606</td>
<td>502</td>
</tr>
<tr>
<td>Young’s Modulus (GPa) [31]</td>
<td>55</td>
<td>35</td>
<td>215</td>
<td>215</td>
</tr>
<tr>
<td>Poisson’s ratio (-) [31]</td>
<td>0.17</td>
<td>0.25</td>
<td>0.32</td>
<td>0.27</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (1/K) [31]</td>
<td>10 x 10⁻⁶</td>
<td>11 x 10⁻⁶</td>
<td>10 x 10⁻⁶</td>
<td>18 x 10⁻⁶</td>
</tr>
</tbody>
</table>

For the fuel and air channels, hydrogen is used as the fuel for this study and air as the oxidant, as listed in Table 5, and are taken from the material library in COMSOL [35]. As stated previously, a benefit of SOFCs is the wide range of fuels that can be used due to the high operating temperature. For this study it was assumed that a fuel processor would be incorporated to reform the hydrocarbon fuel into hydrogen. As such, hydrogen is the fuel that is used during the modeling of the heat up times of the SOFC.
### Table 5: Material properties for air and fuel channels

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Hydrogen</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio of specific heats (-)</td>
<td>1.41</td>
<td>1.4</td>
</tr>
<tr>
<td>Heat capacity (J/(kg*K))</td>
<td>5000</td>
<td>1051</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>0.2</td>
<td>0.58</td>
</tr>
<tr>
<td>Thermal conductivity (W/(m*K))</td>
<td>0.2</td>
<td>0.047</td>
</tr>
</tbody>
</table>

#### 4.4 Meshing

In COMSOL, the meshing can be done by predefining the element quality or can be done manually. For this study, since there is a large difference in thickness versus the length of the geometry, the mesh was manually done, by setting restrictions on the size and how it is distributed. The benefit of this was a more symmetrical meshing was created and allowed for better convergence of the results. The distribution was set to limit the number of elements along the thickness of the geometry to eight, as well as limiting the total number of swept elements to 200. Figure 17 shows a close up of how the model was meshed for this geometry.
The total number of elements in this mesh is 28,600 as well as 16,372 boundary elements. Table 6 shows the characteristics of the mesh used for this model. The mesh allowed for good convergence during the studies and when solving for the heat up time without thermal stress calculations, took 690 seconds to run.

<table>
<thead>
<tr>
<th>Mesh Characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain elements</td>
<td>28,600</td>
</tr>
<tr>
<td>Boundary elements</td>
<td>16,372</td>
</tr>
<tr>
<td>Average element quality</td>
<td>0.8648</td>
</tr>
<tr>
<td>Element volume ratio</td>
<td>1.54E-04</td>
</tr>
<tr>
<td>Computational time</td>
<td>690</td>
</tr>
</tbody>
</table>

A mesh refinement was done, to see how increasing the number of elements changed the results of the study. The mesh refinement study was done using the single channel heat up method, with just the air channel being used to heat the cell. The study used the
100 K maximum temperature difference heat up strategy which is one the studies modeled for this research. Table 7 shows how with increasing elements, the study time increases, on top of a slight change in heat up time.

<table>
<thead>
<tr>
<th></th>
<th>28,600</th>
<th>62,000</th>
<th>93,000</th>
<th>116,400</th>
<th>176,800</th>
</tr>
</thead>
<tbody>
<tr>
<td># of domain elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of boundary elements</td>
<td>16,372</td>
<td>33,820</td>
<td>46,220</td>
<td>49,976</td>
<td>72,884</td>
</tr>
<tr>
<td>Average element quality</td>
<td>0.8648</td>
<td>0.8561</td>
<td>0.7932</td>
<td>0.8698</td>
<td>0.8766</td>
</tr>
<tr>
<td>Element volume ratio</td>
<td>1.54E-04</td>
<td>1.24E-04</td>
<td>2.06E-04</td>
<td>2.63E-04</td>
<td>2.73E-04</td>
</tr>
<tr>
<td>Heat up time (s)</td>
<td>800</td>
<td>786</td>
<td>813</td>
<td>817</td>
<td>793</td>
</tr>
<tr>
<td>Computational time (s)</td>
<td>690</td>
<td>1305</td>
<td>2500</td>
<td>2641</td>
<td>32,985</td>
</tr>
</tbody>
</table>

From Table 7 it can be seen that almost tripling the number of elements in the meshing leads to about double the study time. The average element quality stays similar for all meshes done, and the heat up time stays around 800 seconds. Since for each of the mesh refinement studies done, the heat up times stayed within 2 % of 800 seconds, the meshing that provided the shortest computational time was chosen.
4.5 Model Validation

Before any studies were run on the model, it needed to be validated to confirm that the results presented are accurate. For this research, the model was validated against a model developed by David L. Damm and Andrei Fedorov [28] as well as a finite volume model developed by Ming-Hong Chen, and Tsung Leo Jiang [29]. To validate the model, the physics used in the current COMSOL model was not changed, but the geometry, material properties, and parameters were adjusted to match that of the other models. Table 8 shows the material properties used for the validation, and Figure 18 shows the dimensions of the geometry that is used for the model validation.

<table>
<thead>
<tr>
<th>Component</th>
<th>$k$ (W/(m*K))</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$C_p$ (J/(kg*K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode</td>
<td>5.84</td>
<td>3030</td>
<td>595</td>
</tr>
<tr>
<td>Cathode</td>
<td>1.86</td>
<td>3310</td>
<td>573</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>2.16</td>
<td>5160</td>
<td>606</td>
</tr>
<tr>
<td>Current collector</td>
<td>20</td>
<td>8030</td>
<td>502</td>
</tr>
<tr>
<td>Air Channel</td>
<td>0.047</td>
<td>0.58</td>
<td>1051</td>
</tr>
<tr>
<td>Fuel Channel</td>
<td>0.2</td>
<td>0.2</td>
<td>5000</td>
</tr>
</tbody>
</table>
For the inlet conditions used for the validation, the inlet velocity of the air channel was set to 10 m/s, with the fuel channel being set to 0 m/s to simulate only the air channel being used to heat the cell. No other changes to the parameters were made and were kept the same as the current study.

The validation of the model consisted of 3 simulations each with varying rising inlet temperatures rates (°C/s). The 3 rates chosen for the simulations followed what was done by Chen and Jiang, with the rates being 0.01, .01, and 1 °C/s respectively [29]. The three model simulations were run with the cell starting at a temperature of 25 °C. The time the cell took to reach a minimum cell temperature of 625 °C was measured for each of the three runs. Below, Figure 19 shows the results of the simulations that were done for the model validation.
Figure 19: Heat up times for current model compared with two other models in literature used for validation

From Figure 19, it can be seen that the current model is in good agreement with the other two studies. When the inlet temperature rate is 1 °C/sec there is a slight discrepancy in the result. This can be attributed to the meshing that was required for the COMSOL model. The meshing had to be refined to allow for the initial values to converge correctly when building the model.

5 Single Channel Results

5.1 Introduction

For the first study, the aim is to investigate what the heat up time would be if only the air channel was used to heat the fuel cell, while the fuel channel was left alone. Three different heat up methods are investigated for the single channel study. They are: introducing the hot air at a set temperature, setting a maximum temperature difference throughout the cell, and finally introducing the hot air at a set increasing temperature rate.
For each method, in addition to looking at the heat up time, the temperature gradients at the fuel channel and air channel symmetry line, and the fuel channel and air channel interconnect were measured to provide information on how changing the method of heat up affected temperature gradients. Figure 20 below shows the locations where the temperature gradients are measured.

![Figure 20: Areas of interest within SOFC where temperature gradients were measured for single channel and dual channel studies](image)

Furthermore, how the inlet velocity affected both the heat up time and temperature gradients that occurred in the cell is examined. For the single channel studies, the gas inlet velocity was changed from 5-25 m/s and the temperature gradients and heat up times for each inlet velocity are calculated.
5.2 Results/Discussion

5.2.1 Set Inlet Temperature

Two set temperatures were chosen for the inlet conditions of the air channel; 873 K and 1073 K. The reason these were chosen was to relate to research done by Hanjo, where at 873 K, the chemical reactions begin to occur. As this research investigates what the optimal heat up strategy is right up until the temperature the reactions can occur, these temperatures were chosen. 1073 K was chosen as this would be the temperature that the fuel processor exhaust heat could be introduced to the SOFC at. It should be noted that for the 1073 K case, it was assumed no reactions occur due to the fact the whole cell needs to reach 873 K for reactions to take place.

5.2.1.1 Heat up Times

For the set inlet temperature study, the heat up times are quite low, from just under 500 seconds for the 873 K inlet condition to about 120 seconds for the 1073 K inlet condition. For automotive purposes this is very good, with the cell being able to generate power within 2-8 minutes of the cell being started up. There also is a clear trend in how velocity affects heat up times. For both inlet cases, as the inlet velocities increase, the heat up time decreases. This same trend is seen when looking at the temperature gradients, the higher the inlet velocity, the lower the temperature gradients. This confirms the results found in another research paper that investigates a reduced order transient model of SOFC heating and cooling [28].

5.2.1.2 Temperature Gradients

Once the heat up times were quantified for this heat up method, the next step was to see what the temperature gradients were for both cases. The temperature gradients are what will show whether the heat up times are achievable, since excessively high temperature gradients, will cause the cell to fail due to the high thermal stress. For both set of inlet temperatures, the air channel experienced the highest temperature gradients compared
with the fuel channel, and for both the air channel and fuel channel, the symmetry plane as seen in Figure 20, showed the higher temperature gradients vs along the interconnect side of the channel. Figure 21 shows the temperature gradients at the fuel channel symmetry plane, and Figure 22 shows the gradients for the air channel symmetry plane.

Figure 21: Fuel channel symmetry maximum temperature gradients for single channel heat up with inlet temperature set to 873K for different inlet velocities
From Figure 21 and Figure 22 it can be seen that the air channel experiences gradients of up to 45,000 K/cm right at the inlet, while the fuel channel only experiences gradients up to 500 K/cm. This is to be expected as the air channel is what experiences the forced convection with high air temperatures, while the fuel channel side temperature gradients are caused more via conduction through the fuel cell components. Figure 23 and Figure 24 show the temperature gradients for the 1073 K study and they follow the same pattern as the 873 K studies.
Figure 23: Fuel channel symmetry maximum temperature gradients for single channel heat up with inlet temperature set to 1073K for different inlet velocities.
Between the two studies, both the fuel and air channels experience the same increase in temperature gradients, with the fuel channel experiencing a 32 % increase in maximum the temperature gradients, while the air channel experiences a 33 % increase.

One interesting result from these two studies is the fact that a change in inlet velocity did not have a significant impact on the overall temperature gradients within the cell. One reason for this would be that the fuel cell is introduced to such high temperatures right away, that any affect that velocity would have is negated.
In summarizing this heat up method, while the heat up times are quite optimal for automotive applications, the temperature gradients experienced during the heat up would be too extreme for the cell to survive when comparing them with the design map created by Damn and Federov [28]. There is a high likelihood that the SOFC would not survive this heat up method.

5.2.2 Maximum Temperature Difference vs Set Temperature Heat up Rate

For the next part of the single channel study, the maximum temperature difference heat up rate was compared to the set temperature ramp method to see which one provided the best heat up times and lowest maximum temperature gradients. For the maximum temperature difference heat up method, the temperature difference throughout the cell was kept at a set value for the whole heat up period. The reasoning behind this was that it was theorized that this would allow for quicker heat up times, while keeping the temperature gradients lower than the first heat up method. As with the first method, the velocity effects on temperature gradients and heat up times were also investigated. For this heat up method, four different temperature differences were looked at. They were: 25 K, 50 K, 75 K, and 100 K.

For the set temperature ramp rate heat up method, the cell was warmed by ramping up the inlet temperature by a set temperature per second. This method of control was done as it was hypothesized this would further lower the temperature gradients that occurred throughout the cell, while not significantly sacrificing heat up time, compared to the minimum temperature difference. Five different ramp rates were included in this research; 0.1 K/s, 0.5 K/s, 1 K/s, 2 K/s and 5 K/s. These rates were chosen as they were similar to the ramp rates selected in the papers used for validation [27] [28], and the 2 K/s and 5 K/s rates would have heat up times that were estimated to be around 300 and 125 seconds respectively. Like the previous heat up methods, the temperature gradient plots for both channels were made, as well as heat up times for each of the ramp up rates.
5.2.2.1 Heat up Times

Figure 25 shows the heat up times for both the maximum temperature difference and ramp rate methods and how the inlet velocity changes the heat up times.

![Graph showing heat up times for different inlet velocities and temperature differences.]

**Figure 25: Heat up times for single channel studies at different inlet velocities**

What is interesting by the results is the fact that there is a reduction of heat up time with an increase in the inlet velocity for the minimum temperature difference study, but a negligible change in heat up times with an increase in velocity for the heat up rate. The main reason for this could be the increase in velocity allows for the air channel to heat the cell quicker, but at a certain velocity, the maximum temperature difference controls the heat up time more than the increase in velocity. For automotive purposes, heat up times above 20 minutes (1200 s) are not ideal, so the only studies that would not be feasible, just by looking at heat up times, would be the ramp up rate of 0.1 K/s, 0.5 K/s and the set temperature difference of 25 K. Table 9 shows the heat up times for the studies that have around a 20-minute heat up time.
Table 9: Heat up times for single channel studies less than 20 minutes (1200s)

<table>
<thead>
<tr>
<th>Inlet Velocity (m/s)</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat up rate 1K/s</td>
<td>792</td>
<td>726</td>
<td>706</td>
</tr>
<tr>
<td>Heat up rate 2K/s</td>
<td>484</td>
<td>469</td>
<td>453</td>
</tr>
<tr>
<td>Heat up rate 5K/s</td>
<td>346</td>
<td>325</td>
<td>293</td>
</tr>
<tr>
<td>Maximum Temp diff 50K</td>
<td>1334</td>
<td>1197</td>
<td>1111</td>
</tr>
<tr>
<td>Maximum Temp diff 75K</td>
<td>903</td>
<td>831</td>
<td>685</td>
</tr>
<tr>
<td>Maximum Temp diff 100K</td>
<td>735</td>
<td>609</td>
<td>560</td>
</tr>
</tbody>
</table>

From Table 9, it can be seen that there is a wide range of heat up times, from a maximum of 22 minutes (1334 s) using the temperature difference of 50 K at an inlet velocity of 15 m/s to a minimum of just under 5 minutes (293 s) for the ramp up rate of 5 K/s with an inlet velocity of 25 m/s. However, the temperature gradients need to be shown to ensure that this heat up method will not result in the SOFC failing due to the thermal stress.

5.2.2.2 Temperature Gradients

For the six heat up methods that achieved heat up times of under 22 minutes, the temperature gradients were calculated. This will show which heat up method is the most promising, as with an increase in temperature gradients, the probability of the failure in the cell will increase. When looking at the temperature profiles of the heat up methods,
the expectation that the highest temperature gradients will occur at the inlet of the air channel is confirmed. Figure 26 below shows the temperature profiles for different single channel heat up methods.

![Temperature profile along air channel for single channel studies](image)

**Figure 26: Temperature profile along air channel for single channel studies**

As it can be seen from Figure 26 above, there is a drop in temperature right at the inlet, before leveling off along the length of the channel. The steep drop off in temperature will correspond to higher temperature gradients. Figure 27, Figure 28, and Figure 29 below show the temperature gradients for each of the inlet velocities.
Figure 27: Maximum temperature gradients along air channel symmetry plane for single channel heat up methods with inlet velocity of 15 m/s.
Figure 28: Maximum temperature gradients along air channel symmetry plane for single channel heat up methods at inlet velocity of 20 m/s
Figure 29: Maximum temperature gradients along air channel symmetry plane for single channel heat up methods at inlet velocity of 25 m/s

For all three inlet velocities, the same heat up methods have the highest and the lowest temperature gradients along the air channel. The maximum temperature difference of 100 K produces the highest temperature gradients, while the 1 K/s temperature increasing rate produces the lowest. As well, for the temperature increasing rate, an increase in velocity produces between 14-16 % decrease in temperature gradients depending on the temperature increasing rate. For the maximum temperature difference heat up method, the reduction in temperature gradients is less pronounced, only about 5 % reduction in temperature gradients.
Along the fuel channel is where the lowest temperature gradients occur, and there is very little change in the temperature gradients with a change in inlet velocity. Figure 30 below shows the temperature gradients along the fuel channel with an inlet velocity of 15 m/s, with the plots for 20 m/s, and 25 m/s in Appendix C.

![Figure 30: Maximum temperature gradients along fuel channel symmetry for single channel heat up methods at inlet velocity of 15 m/s](image)

As it can be seen above, the temperature gradients that occur along the fuel channel are very low compared to the air channel, with a maximum value of only 90 K/cm. This is to be expected when taking into account the temperature profile along the anode seen below in Figure 31.
There is very little change in temperature along the length of the fuel channel, with the maximum temperature difference along the length of the channel being less than 50 K. Table 10 below ranks the heat up methods by highest to lowest temperature gradients, with the corresponding heat up times beside.

Figure 31: Temperature profile along fuel channel for single channel studies
Table 10: Ranking of heat up methods by highest to lowest temperature gradients for single channel heat up methods at 20 m/s inlet velocity

<table>
<thead>
<tr>
<th>Heat up Method</th>
<th>Temperature gradients (K/cm)</th>
<th>Heat up time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Temp Diff 100 K</td>
<td>3810</td>
<td>609</td>
</tr>
<tr>
<td>Heat up Rate 5 K/s</td>
<td>2735</td>
<td>325</td>
</tr>
<tr>
<td>Maximum Temp Diff 75 K</td>
<td>2321</td>
<td>831</td>
</tr>
<tr>
<td>Maximum Temp Diff 50 K</td>
<td>1885</td>
<td>1197</td>
</tr>
<tr>
<td>Heat up Rate 2 K/s</td>
<td>1138</td>
<td>469</td>
</tr>
<tr>
<td>Heat up Rate 1 K/s</td>
<td>573</td>
<td>726</td>
</tr>
</tbody>
</table>

From the table above, the most promising heat up methods are the heat up rates of 1 K/s and 2 K/s, as they have temperature gradients of 573 K/cm, and 1138 K/cm respectively, while having heat up times of under 12 minutes. The heat up method with the lowest heat up time, is the 5 K/s ramp rate with a heat up time of under 6 minutes (325 s), has a heat up time of under 6 minutes. However, it produces temperature gradients of over 2700 K/cm which will increase the probability of failure throughout the SOFC. A stress analysis and/or an experimental study will need to be done to confirm whether or not these temperature gradients are feasible to prevent failure in the SOFC.

For how long and at what time during the heat up process the maximum temperature gradients occur is also important when investigating whether the heat up times are achievable. If the temperature gradients occur over a longer period of time, it is more likely that the cell will fail. However, if the temperature gradients only occur for a small
period of time, if the cell can withstand the thermal shock, the heat up method would be more promising. Figure 32 below shows the maximum temperature gradients over time for each of the heat up methods.

![Graph showing maximum temperature gradients over time for single channel studies with inlet velocity of 15 m/s](image)

**Figure 32: Maximum temperature gradients over time for single channel studies with inlet velocity of 15 m/s**

For the maximum temperature difference studies, the maximum temperature gradients occur within 5 seconds of starting the heat up method, and within 25 seconds drops by 75%. By 75 seconds they have leveled off to a level lower than the maximum gradients determined for each of the temperature increasing rate studies. This is important to note, as it shows that if the SOFC can withstand the thermal shock during the 100 K maximum temperature heat up method, it would make this method feasible. This is because the heat up method levels off at temperature gradients lower than the 1 K/s and 2 K/s studies.
Table 11 below ranks the heat up methods by their steady state temperature gradients from highest to lowest.

**Table 11: Steady state temperature gradients for single channel heat up methods ranked highest to lowest**

<table>
<thead>
<tr>
<th>Heat up Method</th>
<th>Steady State Temperature Gradients (K/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat up Rate 2 K/s</td>
<td>1324</td>
</tr>
<tr>
<td>Heat up Rate 1 K/s</td>
<td>667</td>
</tr>
<tr>
<td>Maximum Temp Diff 100 K</td>
<td>588</td>
</tr>
<tr>
<td>Maximum Temp Diff 75 K</td>
<td>443</td>
</tr>
<tr>
<td>Maximum Temp Diff 50 K</td>
<td>300</td>
</tr>
</tbody>
</table>

As it can be seen, the results are flipped when comparing them to the maximum temperature gradients that are achieved during heat up. The heat up rate method produces the highest temperature gradients when comparing them to the maximum temperature heat up method’s steady state temperature gradients. This is important to note because as stated above, if the cell can withstand the thermal shock experienced by the set temperature methods within the first 10 seconds, these heat up methods become a lot more attractive option in regard to temperature gradients. However,
because the heat up times are quite a bit higher than the ramp rates, except for the 100 K study, this would not be beneficial for quick heat up times.

5.3 Conclusion

Introducing the air channels with air at set temperatures of 873 K and 1073 K produces very quick start up times, however the temperature gradients are too extreme for heat up method to be feasible. When looking at the maximum temperature and heat up rate heat up method, five methods produce heat up times of under 22 minutes: Maximum temperature differences of 50 K, 75 K and 100 K, and heat up rates of 1 K/s, 2 K/s and 5 K/s. In regard to temperature gradients, while the maximum temperature difference studies have higher overall temperature gradients when compared to the heat up rate methods, those methods only experience the high temperature gradients within 4 seconds of started the heat up, and within 25 seconds drops by 75 %. Three heat up methods when looking at both temperature gradients and heat up times look promising: the 1 K/s and 2 K/s heat up rate studies, and the 100 K maximum temperature study. These methods produce heat up times of 726 s, 469 s, and 609 s respectively. Because of the fact that the temperature gradients drop so suddenly when using the 100 K temperature difference method, this heat up method would be the most likely to succeed if the SOFC was used for an automotive application.

6 Dual Channel Study

6.1 Introduction

The different scenarios done in the previous section all investigated the heat up time and corresponding temperature gradients with only the air channel being used to heat up the cell. From that study, three heat up methods looked promising when taking into account low temperature gradients and heat up time. They were the 1 K/s, and 2 K/s temperature
increasing rate heat up method, and the 100 K maximum temperature difference heat up method. This study will look at how the heat up times and temperature gradients in the air and fuel channels change when the fuel channel is also used to heat up the cell to the operating temperature. This is done by supplying the fuel channel with the same gas, in this study hydrogen, that is used as fuel for the SOFC, and air for the air channel of the SOFC. For this study, two methods were investigated first; the maximum temperature difference method, and the set temperature ramp rate. For the maximum temperature difference method, temperature difference of 10 K, 15 K, 25 K, 50 K, 75 K and 100 K were looked at. For the ramp rate method, rates of 1 K/s, 2 K/s, and 5 K/s were investigated. These results were then discussed and compared to the single channel study to see how the dual channel heat up method affected temperature gradients throughout the channels and heat up times. Finally, a third heat up method was investigated, introducing the fuel channel with hydrogen at the operating temperature, and the air channel at different heat up rates. This was to simulate again the SOFC being warmed using the burner exhaust heat. The aim of this study was to see how the dual channel differed with the single channel when looking at both the maximum temperature gradients in the cell, as well as the time it takes to reach the operating temperature.

6.2 Results/Discussion

6.2.1 Maximum Temperature Difference vs Temperature Increasing Rate

As stated above, nine different heat up methods were investigated for the dual channel heat up method: 10 K, 15 K, 25 K, 50 K, 75 K, 100 K, 1 K/s, 2 K/s, and 5 K/s. Some heat up methods were looked at to compare them to the single channel heat up methods discussed in Chapter 5. For each of the heat up methods the inlet velocities were set at 15 m/s, 20 m/s, and 25 m/s, just as was done for the single channel studies.
6.2.1.1 Heat up Times

Figure 33 below shows the heat up times for each inlet velocity for all of the dual channel studies investigated.

![Figure 33: Heat up times for all dual channel studies at different inlet velocities](image)

From Figure 33 above, there are many promising studies, when just looking at heat up times. Four studies have heat up times under 500 seconds (8.3 minutes). The studies that have heat up times under 500 seconds, the change in velocity has a negligible effect on heat up times. When comparing the single channel studies to double channel, there is a significant reduction in heat up times for the maximum temperature difference studies compared to a moderate reduction for heat up rate studies. Table 12 below shows the comparison of heat up times for both the single channel and double channel studies.
Table 12: Comparison of heat up times between single channel and double channel for inlet velocity of 20 m/s

<table>
<thead>
<tr>
<th>Heat Up Method</th>
<th>Single Channel Heat Up Time (s)</th>
<th>Dual Channel Heat Up Time (s)</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 K/s</td>
<td>726</td>
<td>626</td>
<td>14%</td>
</tr>
<tr>
<td>2 K/s</td>
<td>469</td>
<td>335</td>
<td>29%</td>
</tr>
<tr>
<td>5 K/s</td>
<td>325</td>
<td>168</td>
<td>48%</td>
</tr>
<tr>
<td>100 K</td>
<td>609</td>
<td>273</td>
<td>55%</td>
</tr>
<tr>
<td>75 K</td>
<td>831</td>
<td>330</td>
<td>60%</td>
</tr>
<tr>
<td>50 K</td>
<td>1197</td>
<td>532</td>
<td>56%</td>
</tr>
</tbody>
</table>

As it can be seen from Table 12 above, the maximum temperature difference heat up method has a 55-60 % reduction in heat up times when using the dual channel heat up method. The 5 K/s temperature increasing rate heat up method is the only rate for that heat up method to achieve a noticeable reduction in heat up times when using the dual channel heat up method, at 48 %.

As done in Chapter 5 the heat up methods that achieved promising times were ranked from highest to lowest. As most heat up methods were below 20 minutes, for the dual channel study, the heat up methods that achieved times under 500 seconds were chosen. Because the 50 K study is close to under 500 seconds with a 20 m/s inlet velocity, and
less than 500 seconds for an inlet velocity of 25 m/s, it has been included in Table 13 below.

Table 13: Summary of heat up times for dual channel studies under 500 seconds

<table>
<thead>
<tr>
<th>Heat up method</th>
<th>Inlet Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15m/s</td>
</tr>
<tr>
<td>2 K/s</td>
<td>365</td>
</tr>
<tr>
<td>5 K/s</td>
<td>187</td>
</tr>
<tr>
<td>100 K</td>
<td>290</td>
</tr>
<tr>
<td>75 K</td>
<td>345</td>
</tr>
<tr>
<td>50 K</td>
<td>722</td>
</tr>
</tbody>
</table>

Looking at Table 13 above, a change in velocity does not have that big of an effect on heat up times, and all heat up methods in Table 13 would be a feasible heat up method just looking at heat up times. The next section will show what the temperature gradients are for each of these methods, to provide a better comparison between these studies.

6.2.1.2 Temperature gradients

Since the fuel channel now contributes with the heat up process, the temperature gradients seen in the fuel channel are higher than that of the single channel studies, which is to be expected, and can be confirmed when looking at the temperature plots when each
heat up rate experiences their highest temperature gradients for the studies seen below in Figure 34:

![Temperature profile along fuel channel for two dual channel maximum temperature difference studies](image)

**Figure 34: Temperature profile along fuel channel for two dual channel maximum temperature difference studies**

As it can be seen from Figure 34 above, with the high temperatures at the inlet of the fuel channel and a sharp decrease along the length of the channel, the temperature gradients at the inlet will be high and the profiles that have less of a change in temperature along the length of the channel will experience less temperature gradients.

For a comparison of the temperature gradients between the single and dual channel studies, the temperature gradients in the air and fuel channels for the maximum
temperature difference of 100 K is shown for both the single and dual channel heat up method below in Figure 35.

![Figure 35: Maximum temperature gradients for 100 K temperature heat up method for both single and dual channel studies with an inlet velocity of 20 m/s](image)

As it can be seen from Figure 35 above, the dual channel heat up method produces moderate temperature gradients for both the fuel and air channel, when compared to the high temperature gradients for the single channel study. This makes the 100 K heat up method for the dual channel more feasible than the single channel study because of the less extreme temperature gradients experienced in the air channel. Figure 36, Figure 37,
and Figure 38 show the air channel symmetry temperature gradients with inlet velocities of 15 m/s, 20 m/s, and 25 m/s respectively.

Figure 36: Air channel symmetry maximum temperature gradients for dual channel heat up methods with inlet velocity of 15 m/s
Figure 37: Air channel symmetry maximum temperature gradients for dual channel heat up methods with inlet velocity of 20 m/s
From Figure 36, Figure 37, and Figure 38 above, it can be seen that the temperature increasing rate studies have the lowest temperature gradients along the air channel compared to the maximum temperature difference studies. This trend is the same along the fuel channel symmetry temperature gradients, as seen below in Figure 39 which shows the temperature gradients along the fuel channel symmetry line with an inlet velocity of 15 m/s. For temperature gradients for the 20 m/s and 25 m/s studies see Appendix D.
As seen in Figure 39 above, for the fuel channel symmetry gradients, the same trend is followed with the temperature increasing rate studies have lower temperature gradients than the maximum temperature difference studies. Looking at the 20 m/s study, Table 14 compares the temperature gradients along the air and fuel channel studies.
Table 14: Comparison of temperature gradients for dual channel studies along air and fuel channel with inlet velocity of 20 m/s

<table>
<thead>
<tr>
<th>Heat up Method</th>
<th>Fuel Channel (K/cm)</th>
<th>Air Channel (K/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 K Max Temp Diff</td>
<td>575</td>
<td>820</td>
</tr>
<tr>
<td>75 K Max Temp Diff</td>
<td>831</td>
<td>1185</td>
</tr>
<tr>
<td>100 K Max Temp Diff</td>
<td>1136</td>
<td>1621</td>
</tr>
<tr>
<td>2 K/s Temp Increasing Rate</td>
<td>95</td>
<td>135</td>
</tr>
<tr>
<td>5 K/s Temp Increasing Rate</td>
<td>240</td>
<td>340</td>
</tr>
</tbody>
</table>

As it can be seen from Table 14, the air channel still experiences the highest temperature gradients, however the fuel channel produces similar temperature gradients, and they are a lot higher than temperature gradients along the fuel channel in the single channel studies, but similar to that of the air channel temperature gradients.

With the significant reduction in heat up time using the dual channel method for the minimum temperature difference heat up method, lower temperature differences can be used, while still maintaining similar heat up times compared to the single channel method. If the twenty minutes threshold is an appropriate heat up time, as used as an appropriate time for the single channel studies, then the 10 K, 15 K, and 25 K maximum temperature difference studies as well as the 1 K/s temperature increasing rate study would become feasible for the dual channel studies. Figure 40 and Figure 41 show the temperature...
gradients for studies with heat up times under or around 20 minutes and with temperature gradients less than the 5 K/s temperature increasing rate study.

Figure 40: Fuel channel symmetry maximum temperature gradients for dual channel studies with heat up times under 20 minutes with inlet velocity of 20 m/s
Figure 41: Air channel symmetry temperature gradients for dual channel studies with heat up times under 20 minutes with inlet velocity of 20 m/s

From Figure 40 and Figure 41 above, all the new studies look promising, as the maximum gradients experienced is less than 300 K/cm along the fuel channel. This is important to note, as from Figure 42 below, the maximum temperature difference studies only stay at their highest temperature gradients for less than 5 seconds, before reaching a steady value less than the 1 K/s and 2 K/s maximum values.
If the fuel cell can withstand the temperature gradients in the cell during the first 3 seconds of the heat up, the maximum temperature difference methods would become more feasible. As the heat up times seen above are relatively similar, ensuring the cell experiences the least amount of temperature gradients is the most important. Table 15 below compares the steady state and maximum temperature gradients for heat up methods that have less than 200 K/cm steady state temperature gradients.
Table 15: Comparison of steady state temperature gradients and maximum temperature gradients with heat up times for dual channel studies

<table>
<thead>
<tr>
<th>Heat up Method</th>
<th>Steady State Temp Gradients (K/cm)</th>
<th>Max Temp Gradients (K/cm)</th>
<th>Heat up Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 K/s Temp Increasing Rate</td>
<td>47</td>
<td>47</td>
<td>626</td>
</tr>
<tr>
<td>2 K/s Temp Increasing Rate</td>
<td>133</td>
<td>133</td>
<td>335</td>
</tr>
<tr>
<td>10 K Max Temp Diff</td>
<td>13</td>
<td>152</td>
<td>1879</td>
</tr>
<tr>
<td>15 K Max Temp Diff</td>
<td>18</td>
<td>236</td>
<td>1295</td>
</tr>
<tr>
<td>25 K Max Temp Diff</td>
<td>37</td>
<td>403</td>
<td>1004</td>
</tr>
<tr>
<td>100 K Max Temp Diff</td>
<td>176</td>
<td>1795</td>
<td>273</td>
</tr>
</tbody>
</table>

As seen from Table 15 above, if the steady state temperature gradients are what will cause the cell to fail, then the maximum temperature difference heat up method is more feasible, but if maximum temperature gradients are more important, then the temperature increasing rate becomes more feasible.

6.2.2 Fuel Channel set at 1073 K with Different Heat up Methods for Air Channel

One final study incorporated what was done for the single channel study, and had the second channel, in this case the air channel, use the 100 K and 1 K/s heat up methods
investigated in the dual channel study, to see if the temperature gradients were any less extreme as in the single channel study. When using the 100 K temperature difference method along the air channel, and the fuel channel set at 1073 K, the heat up times were quite good. It took only 88 seconds for the SOFC to reach its operating temperature. However, when looking below at Figure 43, it can easily seen that the temperature gradients are quite high still.

![Graph showing temperature gradients](image)

**Figure 43:** Dual channel heat up method with fuel channel set to 1073 K and air channel having set temperature difference of 100 K.

The air channel symmetry plane experiences gradients of up to 25,000 K/cm, while the fuel channel symmetry reaches gradients of over 15,000 K/cm. These are not as high as the single channel study, however these are still quite extreme, and the SOFC would not be able to survive with these temperature gradients. Figure 44 below shows the 100 K
study over time as well as including the 1 K/s study to compare how the temperature gradients are different when using these two studies.

Figure 44: Maximum temperature gradients over time with fuel channel inlet set at 1073 K with air channel set at two different heat up methods

As it can be seen from Figure 44 above, the 1 K/s study induces higher temperature gradients reaching almost 30,000 K/cm. As well, even though for the maximum temperature difference of 100 K method, the temperature gradients decrease over time, they do not drop below 5,000 K/cm along the fuel channel until the 45 second mark. The leads to the conclusion that even if the SOFC could survive the initial thermal shock, it still would not survive as the gradients throughout the cell do not decrease fast enough.
6.3 Conclusion

The dual channel heat up method produces drastically reduced heat up times when compared to the single channel heat up method. All heat up methods investigated achieve heat up times close to 20 minutes or less, with four heat up methods; 50 K, 75 K, 100 K, 2 K/s, and 5 K/s achieving heat up times less than 500 seconds.

Temperature gradients along the air channel are lower when compared to the corresponding heat up method for single channel studies, and slightly higher along the fuel channel. The temperature increasing rate heat up methods produce lower temperature gradients than the maximum temperature difference heat up method for studies with heat up times of under 500 seconds.

When using the same time constraint as the single channel heat up method of around 20 minutes, and with a maximum temperature gradient of just under 350 K/cm along the air channel, the 1 K/s, 10 K, 15 K, and 25 K heat up methods become feasible.

When comparing the steady state temperature gradients, all heat up methods studied except the 5 K/s heat up method produce temperature gradients of less than 200 K/cm, and the maximum temperature difference of 100 K becomes the most attractive heat up method. This follows in line with the single channel results, having the 100 K heat up method being the most feasible. As discussed in the single channel results section, having the temperature gradients dissipate drastically after 10-15 seconds, makes this the most likely heat up method to survive the thermal stress created during the heat up.
7 Thermal Stress

7.1 Introduction

Once the different heat up scenarios investigated in the previous two chapters were done, the next part of the research investigated how the heat up strategies affected the thermal stress in the SOFC. For the thermal stress part of the study, the most promising heat up methods when looking at a combination of heat up times and temperature gradients were run with the thermal stress model in COMSOL to see what the values of the thermal stress would be. The aim of this study is to be able to better measure which heat up method is the best to achieve the quickest heat up times, while ensuring the structural integrity of the SOFC.

7.2 Results/Discussion

The first thermal stress study looked at the single channel heat up scenarios that were the most promising in regard to heat up times and their temperature gradients. As discussed in section 4 Current Model Overview, the thermal stress is calculated by using the temperature of the material, reference temperature and using the stress-strain relationship. For SOFCs, this reference temperature is usually the assembly temperature, 1073 K. Because of this, when the thermal stress is calculated for each heat up method, the residual stress has a more dominant effect compared to the temperature profile of each heat up method. Some research has stated that temperature gradients only account for 30% of the overall thermal stress [6]. This trend was the same for both the single channel and dual channel heat up methods, and Figure 45 and Figure 46 show the resulting stress for the dual channel studies when the reference temperature is set to 1073 K.
Figure 45: Thermal stress for dual channel studies along anode when the temperature gradients of the maximum temperature difference methods are highest
The stress was calculated when the temperature gradients were highest for the maximum temperature difference studies, which was two seconds. This was because when residual stress is calculated, the stress profile stays the same no matter the time, only the values of the stress change. The only thing that affects the magnitude of the stress is the temperature values. So, the higher the temperature throughout the cell the lower the stress.
Since the thermal stress during the heat up process is dominated by the residual stress when temperature gradients are highest, the thermal stress was calculated neglecting the residual stress, so that the impact of the temperature profile can be more pronounced. The stress was calculated at two different time steps; 2 seconds, when the temperature gradients are highest for the maximum temperature difference method, and 10 seconds, when the ramp rate experiences higher temperature gradients. Figure 47, and Figure 48 show the thermal stress for the single channel studies at the two second mark during the heat up.

![Figure 47: Thermal stress along anode for single channel heat up methods at 2 s without residual stress](image)

Figure 47: Thermal stress along anode for single channel heat up methods at 2 s without residual stress

82
As expected, the highest thermal stress occurs for the temperature difference studies because they experience the higher temperature gradients at this time step. When comparing the cathode and the anode, the cathode experiences the higher thermal stress overall when compared to the anode, due to the air channel being what is used to heat up the cell.

Figure 48: Thermal stress along cathode for single channel heat up methods at 2 s without residual stress
Figure 49: Thermal stress along anode for dual channel heat up methods at 2 s without residual stress
For the dual channel heat up method, the cathode had a lower thermal stress, approximately 6 MPa less overall right at the inlet, while the anode experiences higher thermal stress. What is interesting to note is while the at the inlet the temperature gradients cause there to be a spike in the thermal stress, the maximum stress at the 2 second mark is still in the middle of the cell. One reason for this could be that the TEC difference throughout the PEN layer causes more of an impact on the thermal stress along the anode when residual stress is neglected.
Next the thermal stress at the 10 second mark was investigated. This was because at this point during the heat up process, the ramp rate experiences higher overall temperature gradients than the maximum temperature difference method. Figure 51 and Figure 52 show the thermal stress in the anode and cathode respectively at the 10 second mark for the single channel heat up methods.

![Figure 51: Thermal stress along anode for single channel heat up methods at 10 s without residual stress](image)

Figure 52: Thermal stress along cathode for single channel heat up method at 10 s without residual stress

From Figure 51 and Figure 52 above, it can be seen that by the 10 second mark during the heat up, the temperature gradients do not have as pronounced effect on the thermal stress as the difference in temperature from the reference temperature, and the TEC mismatch experienced throughout the SOFC. As expected, the ramp rate experiences higher thermal stress in the cathode right at the inlet of the air channel then the maximum temperature difference method because of higher temperature gradients. Figure 53 and Figure 54 show the thermal stress along the anode and cathode at the 10 second mark neglecting the residual stress for the dual channel studies.
Figure 53: Thermal stress along anode for dual channel heat up methods at 10 s without residual stress
For the dual channel studies, there is not a noticeable spike in thermal stress in either the anode or cathode. This points to the temperature gradients not being as relevant as the stress caused by the TEC mismatch. There is a large difference in the thermal stress along the anode compared to the cathode, which follows the same pattern for the single channel heat up methods seen above in Figure 51 and Figure 52.

7.3 Thermal Stress Conclusion

While the stress is in the same magnitude and similar values as what is in literature, the results do not help distinguish which heat up method is the best. This is because the
residual stress is what dominates the model, and with it included the impact of the temperature profile cannot be readily seen. As the residual stress is what dominates the model, the best that can be done is confirm that with higher temperature gradients, the thermal stress will be higher, as seen from the figures when residual stress is not included in the model. The trends seen in the thermal stress model follows that of the temperature gradients. The higher the temperature gradients, the higher the thermal stress will be. However, because temperature gradients only account for part of the overall thermal stress, the impact they have on the overall thermal stress is lower than that off the effect of residual stress and TEC mismatch.

8 Conclusion

The goal of this research was to investigate the heat up times of a SOFC to be used for automotive applications. Two different types of heat up methods were investigated in this research, single channel and dual channel. Within each method, there were different heat up scenarios investigated looking at the heat up times of each as well as the temperature gradients. For the single channel studies, introducing the air channels with air at set temperatures of 873 K and 1073 K produces very quick start up times of 500 and 120 seconds respectively. However, with temperature gradients of over 45,000 K/cm, this heat up method would not be feasible. Three heat up methods when looking at both temperature gradients and heat up times look promising: the 1 K/s and 2 K/s heat up rate studies, and the 100 K maximum temperature study. These methods produce heat up times of 726 s, 469 s, and 609 s respectively.

For the dual channel heat up methods, like the single channel method, when introducing the fuel channel with gas at 1073 K, while incorporating either the 100 K or 1 K/s heat up method in the air channel produces very good heat up times of only 88 seconds, but temperature gradients exceed over 20,000 K/cm along the air channels to be feasible.
All heat up methods investigated using the dual channel heat up method achieve heat up times close to 20 minutes or less, with four heat up methods; 50 K, 75 K, 100 K, 2 K/s, and 5 K/s achieving heat up times less than 500 seconds.

Temperature gradients for the dual channel studies along the air channel are lower when compared to the corresponding heat up method for single channel studies, and slightly higher along the fuel channel. The increasing temperature rate heat up methods produce overall temperature gradients that are at least 58% lower than the maximum temperature difference heat up method depending on the study with heat up times of under 500 seconds.

When using the same time constraint as the single channel heat up method of around 20 minutes, and with a maximum temperature gradient of just under 350 K/cm along the air channel, the 1 K/s, 10 K, 15 K, and 25 K heat up methods become competitive with similar temperature gradients.

Finally, when incorporating the thermal stress portion of the model, the thermal stress model is dominated by residual stress at values of around 550 MPA, no matter the heat up method used. When residual stress is not included in the model, the same trends are followed as seen in the temperature gradient plots; the higher the gradients, the higher the thermal stress. For the single channel studies, the maximum stress is just over 16 MPa, and for the dual channel studies, 10 MPa.

If SOFCs were used in automotive applications, they would need to have quick and competitive heat up times when compared to other technologies used in this sector. From the results in this research, depending on the heat up method chosen, it takes anywhere from 5-20 minutes to heat up the SOFC to its operating temperature. These times, while not instantaneous, allows SOFCs to be a valid option for automotive applications. A dual channel heat up method with a fixed temperature difference of 100 K will provide a heat up time of 273 seconds and develop thermal stresses of 15 MPa along the anode. This method should provide a suitable means to heat an SOFC to sufficient operating
temperature without generating severe thermal stresses. With today’s technology, and the ability for remote starting and self-driving abilities, having SOFC vehicles automatically start at certain times in the morning, overcomes the longer heat up times when compared to traditional internal combustion vehicles. Once the vehicle is parked, the SOFC can continue to operate to allow for the charging an onboard battery to provide extended range for the next trip.

9 Recommendation and Future Work

It is recommended that to confirm any trends seen during the research, experimental studies with a SOFC test stand are needed. This will allow for a more accurate validation as to the maximum value of temperature gradients that can be sustained during the heat up process of an SOFC. This also will allow there to be a bridge between thermal stress and temperature gradients, so that the highest temperature gradients seen in an SOFC before failure can be better quantified. This can be done by using an SOFC test stand that heats up unit cells using the heat up methods discussed in this research. Using thermocouples, the actual temperature of the cell can be measured and compared with the predicted temperature under similar heating conditions. This would allow for a better confirmation as to whether these results are accurate, and an SOFC would survive the heat up methods.

Research into the material property effects on temperature gradients and stress can also be done using this model. As the TECs of the components in the SOFC are what causes the most thermal stress, research into minimizing the mismatch throughout the cell can be done to try and lower the thermal stress during the heat up.

Finally, a more detailed thermal stress model could be developed to allow for a better analysis on the effects of the residual stress, temperature profile, and TEC has on the overall thermal stress of a SOFC during the heat up process. Changing the material
properties of the components and analyzing the effects on the overall thermal stress, as well as investigating ways to lower the residual stress of the SOFC are a few studies that could be done. Using a dedicated FEA software like ANSYS would allow for a far more detailed stress model and could incorporate stack modelling as well.
REFERENCES


[34] Saki Honjo, "Inlet Gas Temperature and Velocity Effects on the Thermal Behaviour of Solid Oxide Fuel Cells within an Accelerating Vehicle," MASc thesis in mechanical engineering, University of Guelph, Guelph, ON, 2017

[35] COMSOL Multiphysics, Material Library, 2018

## APPENDICES

### 10 Appendix A- Average Commuting times across Canada

Table 16: List of average commuting times across Canada

<table>
<thead>
<tr>
<th>Area</th>
<th>Car, truck or van (minutes)</th>
<th>Public transit (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Canada</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Largest CMAs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Montréal, Que.</td>
<td>26.8</td>
<td>44.4</td>
</tr>
<tr>
<td>Toronto, Ont.</td>
<td>30.3</td>
<td>49.5</td>
</tr>
<tr>
<td>Vancouver, B.C.</td>
<td>27.3</td>
<td>43.6</td>
</tr>
<tr>
<td><strong>Large CMAs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Québec, Que.</td>
<td>21.2</td>
<td>35.1</td>
</tr>
<tr>
<td>Ottawa–Gatineau, Ont./Que.</td>
<td>24.7</td>
<td>42.2</td>
</tr>
<tr>
<td>Ottawa–Gatineau (Quebec part)</td>
<td>25.9</td>
<td>41.0</td>
</tr>
<tr>
<td>Ottawa–Gatineau (Ontario part)</td>
<td>24.2</td>
<td>42.4</td>
</tr>
<tr>
<td>Winnipeg, Man.</td>
<td>22.6</td>
<td>35.7</td>
</tr>
<tr>
<td>Calgary, Alta.</td>
<td>24.1</td>
<td>41.6</td>
</tr>
<tr>
<td>Edmonton, Alta.</td>
<td>24.2</td>
<td>40.2</td>
</tr>
<tr>
<td><strong>Greater Golden Horseshoe CMAs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peterborough, Ont.</td>
<td>22.8</td>
<td>36.6</td>
</tr>
<tr>
<td>Oshawa, Ont.</td>
<td>30.9</td>
<td>64.1</td>
</tr>
<tr>
<td>Hamilton, Ont.</td>
<td>26.7</td>
<td>50.0</td>
</tr>
<tr>
<td>St. Catharines–Niagara, Ont.</td>
<td>21.4</td>
<td>30.4</td>
</tr>
<tr>
<td>Kitchener–Cambridge–Waterloo, Ont.</td>
<td>22.1</td>
<td>40.3</td>
</tr>
<tr>
<td>Brantford, Ont.</td>
<td>23.9</td>
<td>42.9</td>
</tr>
<tr>
<td>Guelph, Ont.</td>
<td>23.3</td>
<td>43.0</td>
</tr>
<tr>
<td>Barrie, Ont.</td>
<td>30.3</td>
<td>56.5</td>
</tr>
<tr>
<td><strong>Mid-sized CMAs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halifax, N.S.</td>
<td>22.5</td>
<td>39.0</td>
</tr>
<tr>
<td>London, Ont.</td>
<td>21.2</td>
<td>35.7</td>
</tr>
<tr>
<td>Windsor, Ont.</td>
<td>18.8</td>
<td>36.4</td>
</tr>
<tr>
<td>Regina, Sask.</td>
<td>17.3</td>
<td>32.2</td>
</tr>
<tr>
<td>Saskatoon, Sask.</td>
<td>18.7</td>
<td>34.4</td>
</tr>
<tr>
<td>Victoria, B.C.</td>
<td>21.2</td>
<td>34.9</td>
</tr>
<tr>
<td><strong>Small CMAs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sherbrooke, Que.</td>
<td>18.6</td>
<td>29.2</td>
</tr>
<tr>
<td>Trois-Rivières, Que.</td>
<td>18.9</td>
<td>30.0</td>
</tr>
<tr>
<td>Belleville, Ont.</td>
<td>19.6</td>
<td>35.0</td>
</tr>
<tr>
<td>Abbotsford-Mission, B.C.</td>
<td>26.2</td>
<td>45.9</td>
</tr>
<tr>
<td><strong>Other small CMAs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saguenay, Que.</td>
<td>17.2</td>
<td>29.6</td>
</tr>
<tr>
<td>St. John's, N.L.</td>
<td>18.1</td>
<td>33.1</td>
</tr>
<tr>
<td>Moncton, N.B.</td>
<td>16.4</td>
<td>33.1</td>
</tr>
<tr>
<td>Saint John, N.B.</td>
<td>20.0</td>
<td>31.5</td>
</tr>
<tr>
<td>Kingston, Ont.</td>
<td>19.9</td>
<td>30.1</td>
</tr>
<tr>
<td>Greater Sudbury, Ont.</td>
<td>20.4</td>
<td>34.7</td>
</tr>
<tr>
<td>Thunder Bay, Ont.</td>
<td>16.5</td>
<td>31.9</td>
</tr>
<tr>
<td>Lethbridge, Alta.</td>
<td>16.1</td>
<td>35.9</td>
</tr>
<tr>
<td>Kelowna, B.C.</td>
<td>18.9</td>
<td>33.7</td>
</tr>
</tbody>
</table>
11 Appendix B- Reynolds Number Calculation

Below are the Reynolds number calculations for each of the inlet velocities used in the air channels.

**Table 17: Constant values used for Reynolds number calculations**

<table>
<thead>
<tr>
<th>Density of Air at 873 K (kg/m³)</th>
<th>Channel Height (m)</th>
<th>Channel Width (m)</th>
<th>Hydraulic Diameter (m)</th>
<th>Dynamic Viscosity of air at 873 K (kg/m*s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>1.5x10⁻³</td>
<td>4x10⁻³</td>
<td>2.2x10⁻³</td>
<td>3.07x10⁻⁵</td>
</tr>
</tbody>
</table>

**Table 18: Reynolds number for air inlet velocities**

<table>
<thead>
<tr>
<th>Air Velocity (m/s)</th>
<th>Reynolds Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>716.61</td>
</tr>
<tr>
<td>20</td>
<td>573.29</td>
</tr>
<tr>
<td>15</td>
<td>429.97</td>
</tr>
<tr>
<td>10</td>
<td>286.64</td>
</tr>
<tr>
<td>5</td>
<td>143.32</td>
</tr>
</tbody>
</table>
Appendix C- Maximum Temperature Gradients along Fuel Channel Symmetry for Single Channel Studies

The following figures show the maximum temperature gradients along the fuel channel at inlet velocities of 20 and 25 m/s respectively.

Figure 55: Maximum temperature gradients along fuel channel symmetry for single channel heat up methods at inlet velocity of 20 m/s
Figure 56: Maximum temperature gradients along fuel channel symmetry for single channel heat up methods at inlet velocity of 25 m/s
Figures below show the Maximum temperature gradients along the air channel symmetry with inlet velocities of 20 and 25 m/s.

Figure 57: Air channel symmetry maximum temperature gradients for dual channel heat up methods with inlet velocity of 20 m/s
Figure 58: Dual Channel Fuel Channel Symmetry Temperature Gradients with inlet velocity of 25m/s