Numerical Investigation on a Heat Recuperator: Straight vs Wavy Geometry

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Executive Summary

Problem Statement:

Heat recuperators are of extreme importance for energy/power production. Axial heat conduction plays a crucial role on the design/optimization of the heat recuperators. The thickness of the separating plate must be enough to withstand the pressure differences but not more than that to limit the axial heat conduction. How would a wavy channel RHEX compare against a straight one? How is the AM in a straight channel?

Method:

Numerical solution was conducted on MSC Marc-Mentat software. The same working fluid and surrounding material were used in the analysis to allow a fair comparison between a straight and wavy geometry.

Solution:

The wavy geometry did not outperform the straight geometry. The waviness did show to allow shorter RHEX designs but not necessarily lighter. Further analysis on the hydrodynamic aspects needed to be carried out.

Team Members and responsibilities.

Erick G. Moreno Resendiz: He ran various simulations and interpreted the results. He wrote the report. Determined the geometry and working fluid for the simulation. He helped with the additive manufacturing simulation.

Javed Akthar: He ran various simulations and interpreted the results. He helped writing the final report. The team member oversaw the additive manufacturing simulation.

Introduction

In the simple Brayton cycle, very hot fluid exits the combustion chamber, and only a very low fraction of this energy is used to power the turbine; therefore, there is a lot of heat that is being wasted [1], heating the surroundings . In the other hand, if a heat exchanger is included, this heat that would end up wasted otherwise could be used to preheat the airflow that is entering the combustion chamber thus increasing the combustion efficiency hence the overall efficiency of the cycle.

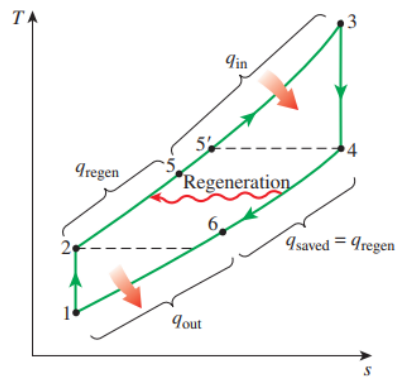

Figure 1. T-s Diagram of a Brayton Cycle with HEX. Image retrieved from [2]

Besides the simple Brayton cycle, there are also several other thermodynamic cycles that can take advantage of the HEXs. The simple Kalina cycle is another example of how recovered heat (via a HEX) can even run a separate cycle to generate power.

Heat exchangers (HEX) are elements designed to attain thermal equalization between two mediums. By taking advantage of the temperature difference, heat is transferred from a hot medium to another cold medium [2]. Given that the HEX are an interface between different parts of a power cycle, considerable pressure difference might exist and need to be managed correctly. The mere addition of a heat exchanger (regardless of their type) to any power cycle will represent an increase in efficiency. They are mainly used in power cycles to convert potential Q_{loss} into Q_{in}. There exist essentially two types of heat exchangers: regenerators and recuperators.

The regenerator HEX stores a hot fluid in a thermal storage medium, the heat is transferred to these high thermal mass components. The now-warm fluid then leaves the medium letting the cold fluid to enter and be in contact with the hot thermal storage medium increasing its temperature. A big disadvantage of this type of heat exchanger is that intrinsic fluid mixing will occur in the process and the losses of exergy which yield to relatively low effectiveness values (<90%).

The recuperator HEX (RHEX) permits the heat transfer to occur entirely separated. A metal plate is placed between the two fluids and as they flow, the heat transfer occurs. The disadvantage of this type is that the area by volume that is involved into the heat transfer is smaller compared to the regenerator implying that to attain the same heat fluxes a bigger component is required.

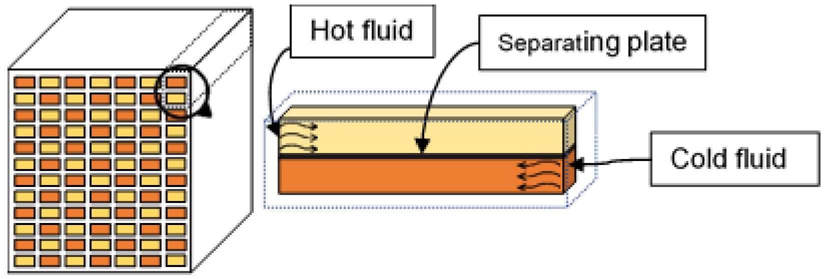

Figure 2. RHEX example. Single element (right)

The selection of the working fluid of the thermodynamic cycle/HEX is crucial for the performance; this selection will depend on the operating ranges and expected outcome of the device. There exist many algorithms to determine the optimum combinations, for instance one can prescribe the inlet properties, fix another constraint, and see what outcome is manufacturable, lighter, cheaper, more efficient thermodynamically speaking or whatever is the design constrain. The manufacturing part of the HEX has progressed a lot with the development of additive manufacturing (AM). Now, more complex and versatile geometries can be manufactured as a single piece which remove the intrusive joints (e.g. brazing joints) that are a possible source of structural failure [3], [4] as well as possible sources of high pressure drop.

It is well known that titanium is highly compatible for additive manufacturing. Titanium possesses many ideal characteristics to serve as the separating material in RHEX such as: relatively low thermal conductivity (k), low density (ρ), high structural resistance (E, σ). It might result counterintuitive but high thermal conductivity yields to an effectiveness deterioration in RHEXs. This is because having such a quick heat transfer will trigger an undesirable effect called: axial heat conduction. The axial heat conduction causes the temperature difference between the fluids to decrease, thus decreasing the rate of heat transfer [5].

Up to date an algorithm that contemplates all the variables does not exist. One might perform an entropy optimization on the HEX, but this will just provide a theoretical option that might cost an exorbitant amount of money or that might be meters in size. Another alternative is to focus entirely on the heat transfer side and obtain an effective design, nonetheless, the structural integrity might be compromised.

Failing to design the structural components might cause an unbalance within the HEX due asymmetric deformation/deflection. Flows will tend to go through the path of less resistance, therefore, if an unseen deflection appears on a given channel then this flow might tend to reverse causing a sudden drop in performance and possible failure.

Regardless of the approach, numerical analysis is still required to couple the different physics and obtain a reliable, high performant and feasible design. Contemplating how all the physics interact with each other is crucial and this can only be done numerically.

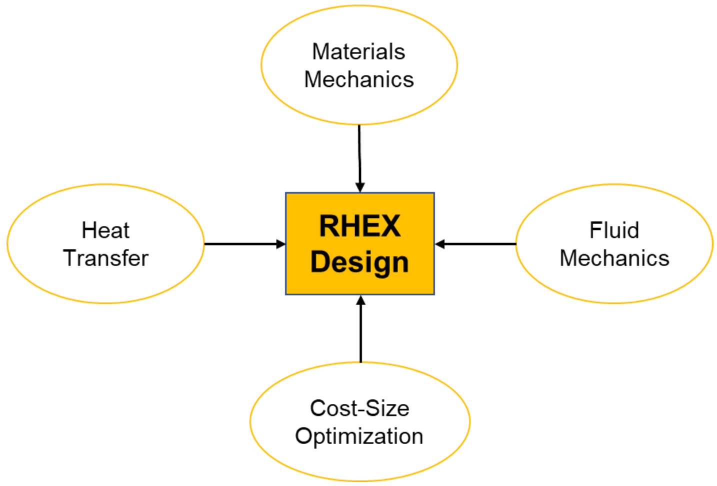

Figure 3. Considerations for designing a RHEX correctly.

In the present work, the NTU-ε method was used. For this method, the inlet and the outlet properties (pressure, temperature, mass flow rate) are fixed, and then the analysis is performed for various working fluids varying the material and as well as the geometric parameters (e.g. number of channels, channel dimensions, length of channel), the outcome of this method is effectiveness. With this effectiveness one can determine if the resultant design is worth manufacturing or not. The designer may opt for a lower effectiveness HEX if another design constraint is considered.

Justification

The world is paying more attention to nuclear power (fission) and power plants in general. The idea of miniaturizing such a valuable and powerful concept opens whole new possibilities in many fields such as: transportation, energy conversion and space exploration. The most used thermodynamic cycle to support the energy conversion from the nuclear plants is the closed Brayton cycle (CBC) power converter. The CBC was found to provide reliability, good efficiency, and the ability to operate selfsustained during long periods. Due the nature of the CBC, makes the RHEX to be ideal for this application; therefore, the current work will focus on the RHEX as they show to have more promising applications compared to the regenerative HEX.

The performed analysis will serve to understand the RHEX in more detail as well as to visualize how the AM would be on it. The analysis of the residual stresses due the additive manufacturing is something that has not been fully investigated.

With the development of the AM, a lot of research is being done on the RHEX geometry side. If the heat transfer performance can be increased, then more compact (lighter) RHEX designs can be conceived. A possibility to attain this objective is to add waviness to the channels to increase the effective surface area per length.

Scope

The project consists of two independent analysis. The heat transfer and the additive manufacturing analysis. The first one would allow to justify the addition of a wavy interface. The second analysis will provide more information about the residual stress (stress state) of the manufactured part.

Heat Transfer

The scope of the current work is to analyze a single element (pair of channels) and obtain the heat transfer performance. The obtained performance will be compared against a wavy geometry to measure the impact the waviness would have.

Additive Manufacturing

The residual stress due the high temperature gradient will be compared in both the geometries.

No extremely fine elements can be used due the required computational time therefore a certain offset is expected and valid.

Implementation

Designing a RHEX based only on heat transfer performance would yield to geometries where W>>H (see Figure 3) (two infinitely long parallel flat plates). Structurally speaking that is not feasible due to the high deflections caused by the pressure difference. In the NTU-ε method, a simple structural criterion on deflection is introduced to avoid these solutions, a fixed thickness is prescribed. Then, it is determined if at the midspan of the plate, considering the pressure difference, the deflection exceeds 1/10 of the thickness, if this occurs then the obtained answer is ignored. Four different separating materials (SS 304, Cu, Al6061 and Titanium alloy) were compared, and the resultant was Titanium alloy (Ti6Al4V).

Another important aspect to consider is the fact that the RHEXs operate at large temperature differences along long tubes, the fluid is transferring heat at relatively high heat rates and therefore changing its properties as it flows; non-isothermal properties should be considered for a more accurate result. The entire analysis was done only for Nitrogen as the working fluid. The main reason is that many power cycles operate with air, and air is 78% Nitrogen. The non-isothermal (isobaric) properties were obtained from National Institute of Standards and Technology (NIST) website at constant pressures.

All the operating properties were obtained based on theoretical applications of the RHEX and introduced to a MATLAB program to estimate a "good" geometry. The obtained parameters are summarized in Table 1. These parameters served to draw the single element into the MSC software.

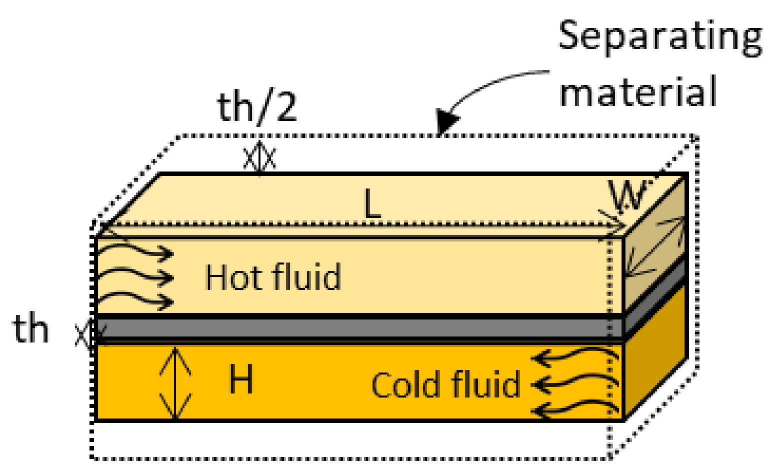

Figure 4. Schematic of the present element. Width (W), Length (L), Height (H), Thickness (th). Surrounding material only applies mainly for AM.

Parameter	**Value**
Working Fluid	Nitrogen
Separating Material	Ti6Al4V
Length (m)	0.5
Width (m)	9.4e-3
Height (m)	2.3e-3
W/H	~4

Thickness (m)	1e-3
Inlet pressure hot (atm)	3
Inlet temperature hot (°C)	130
Average Velocity hot (m/s)	0.4
Inlet pressure cold (atm)	1
Inlet temperature cold (°C)	20
Average Velocity cold (m/s)	0.9

Table 1. Used parameters. The following parameters were obtained from a MATLAB code developed for an ongoing research.

Heat Transfer Model

3D Model

A 3D model was firstly developed given that the proposed W/H ratio was not greater than 10 and therefore a 2D analysis would not be entirely valid or publishable. The discretization was thought on the importance and size of the part. It was also tried to have elements that are not so distorted (aspect ratio distortion) but given the big length (L>>W,H) of the RHEX it would require an excessive number of elements and therefore days or even weeks to solve in a regular computer.

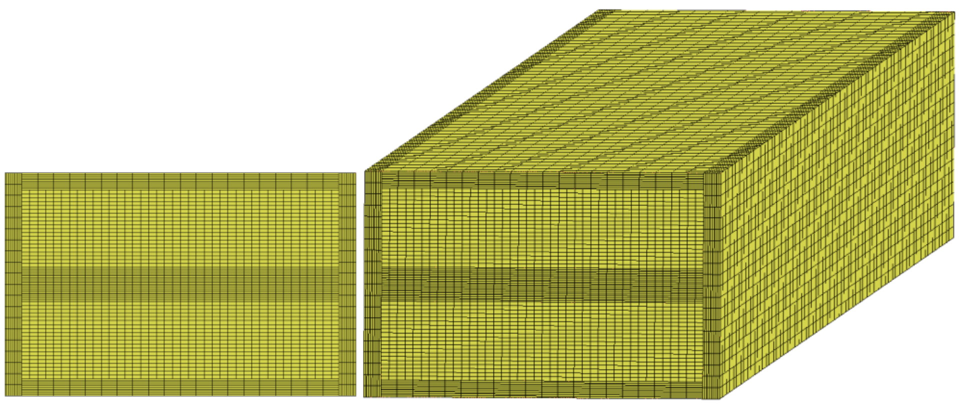

Figure 5. Discretized 3D model of RHEX. This model has 320,000 hex (8) elements and 340,673 nodes.

For the fluid non-isothermal properties 4 tables per flow were created. The properties were: density, specific heat, viscosity and thermal conductivity. No non-isothermal properties were required for the separating material because the properties of the titanium practically do not vary at the used temperature range (10-150°*C)).*

The initial conditions (IC) consisted of an initial temperature that is not relevant, it could be slightly cooler or hotter than the cold fluid; an initial velocity of 0 for both the fluids assuming the flow has just initialized.

The boundary conditions (BC) were the same parameters what were fixed to obtain the optimized geometry (inlet temperature, pressure, and velocity). These were assigned in the form of “thermal fixed temperature” and “fluid fixed pressure” on the first column of nodes for both inlets. For the velocity BC the nodes that are shared with solids were omitted to respect the no slip condition (boundary layer theory).

The structural boundary conditions were more complicated because a single pair of channels is being extracted from an entire system compound by thousands. To take into account for this, the perpendicular displacement to the plate's nodes was constrained. In other words, if the plate lies on the x-y plane then the z displacement for all the nodes of that plate are set to zero. For the middle plate, the nodes located at the outline were fixed in all directions (x,y,z) emulating a fixed-fixed beam, which is similar to the threshold used for avoiding the two infinite parallel plates solution (W/H>>1).

2D Model

Straight Channel

For the 2D model, a similar approach was done with the big difference that the discretization could be finer avoiding the aspect ratio distortion.

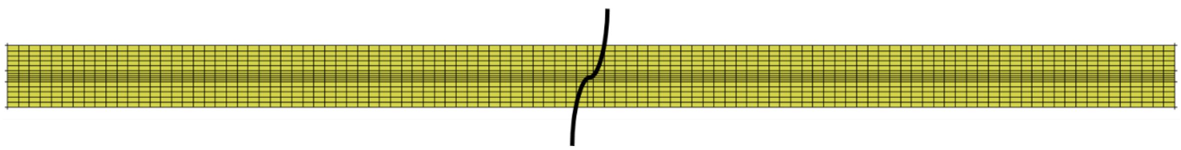

Figure 6. Discretized 2D model. The model has 7500 quad (4) elements and 8016 nodes. The black curve indicates the image was modified for a better visualization.

Due to the nature of the 2D analysis it is impossible to assume this is indeed part of bigger system. The BCs constraining the displacement along the perpendicular directions cannot be included, only the first and last part of the separating plate were constrained in all directions. The ICs were the same as for the 3D model. The initial conditions were the same as for the 3D model.

Wavy Channel

The curve describing the wavy channel is given by: $y = A * \sin\frac{2\pi x}{\lambda}$, this function correspond to a wave with crests and troughs facing each other alternately (serpentine channel) where A=amplitude and λ=wavelength. An arbitrary amplitude of 1mm and wavelength of 31.25mm. The values were chosen based on visual inspection; the wave cannot be too steep because it would yield to flow separation (high pressure drop) but it should be steep enough to take advantage of the velocity profile shift. The obtained channel looks "streamlined" therefore it can be said it will not have much pressure drop.

The wave was firstly created on excel, then exported to SOLIDWORKS to finally be imported to MSC software. It was seen again that the geometrical constraint L>>W,H was distorting the mesh. The boundary conditions were the same as for the straight 2D channel.

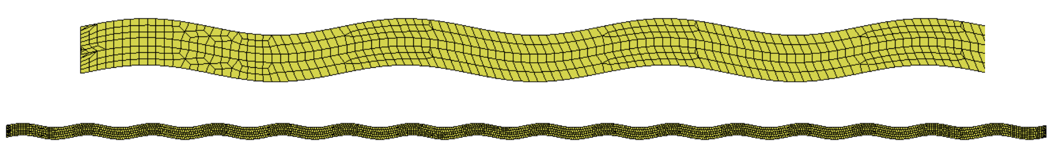

Figure 7. Discretized 2D model of wavy configuration. The model has 3042 quad (4) elements and 3522 nodes.

Additive Manufacturing Model

The AM model needed some modifications with respect to the heat transfer 3D model. The fluid chamber must be empty because only the surrounding material is being analyzed. For this part most of the information was taken from ME518 Finite Element Analysis Lab08 practice. Given that for this analysis very high temperatures (1200 *°C)* in very short lapses of time, non-isothermal properties should be used for the Titanium.

To make the analysis computationally lighter only a small segment of the channel (length 50 µm) was simulated. It is believed that due to the prolongated cooling, in addition to the fact that L>>W,H this assumption will not affect the results substantially.

The specimen was divided into 50 segments (1 µm each) which would "simulate" what the laser is melting.

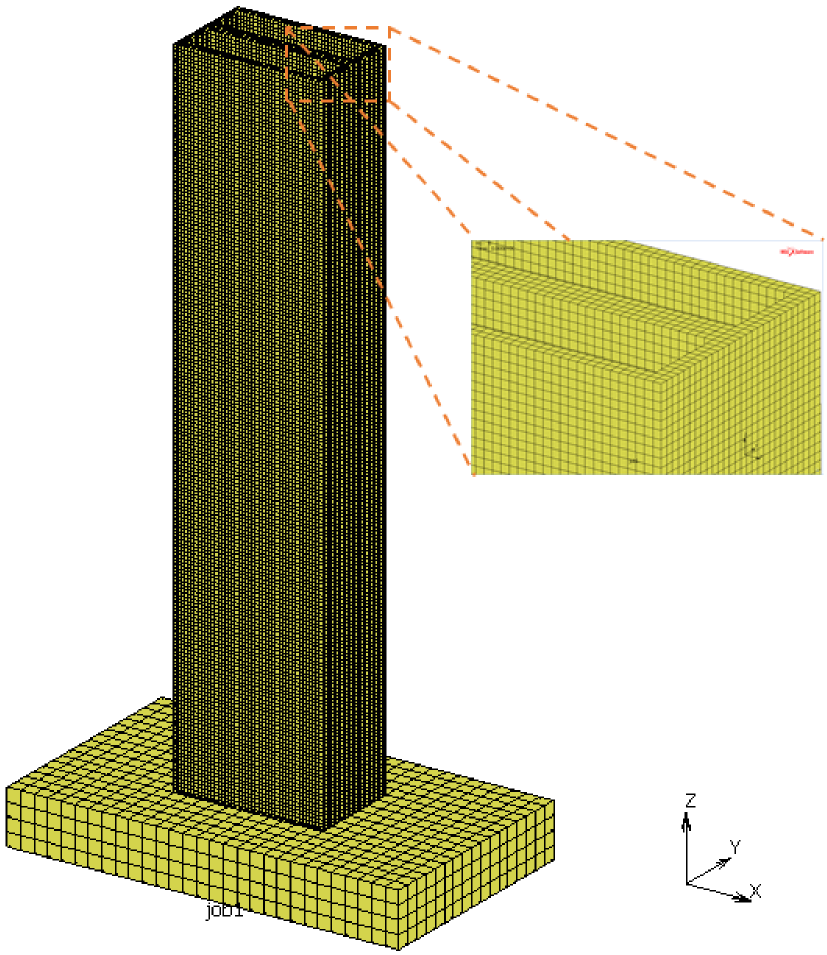

Figure 8. Discretized 3D model. The model has 88372 hex (8) elements and 123847 nodes.

Validation

The validation would imply comparing the heat transfer performance at the steady state of the straight channel with the result from the code. The code predicted a 0.99 of effectiveness. In other words, the 99% of the temperature difference has been transferred.

Outlet (counterflow)	Predicted Temperature *(°C)*	Numerical Temperature *(°C)* *(2D)*	Error % (computed in Kelvin) (2D)
2D			
Hot (x=0.5 m)	20.73	39.5	6.3%
Cold (x=0 m)	129.547	110.5	4.73%
3D			
Hot (x=0.5 m)	20.73	21.74	0.3%
Cold (x=0 m)	129.547	128.3	0.3%

Table 2. Predicted temperature vs numerical temperature.

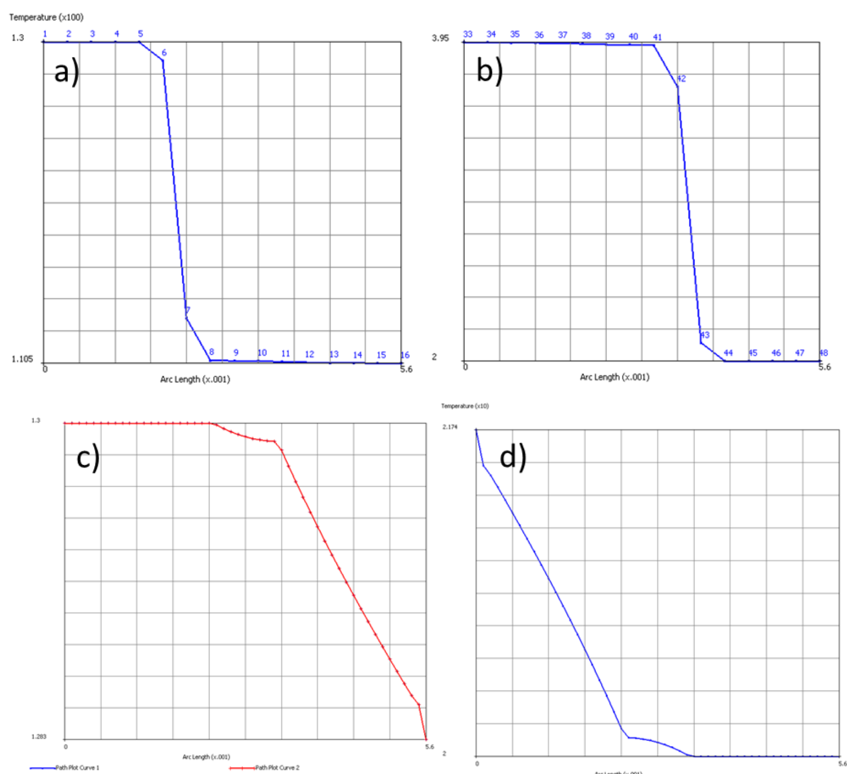

Figure 9. Numerical estimation of the outlet temperatures of the channels. a)2D cold outlet, b)2D hot outlet c)3D cold outlet, d)3D hot outlet.

Strangely, the 2D case reports a lower effectiveness regardless of the assumption of two infinite parallel plates. This suggests that there is something wrong either with the theoretical or the numerical model. The 3D results perfectly match with the code, it would imply that the answers are correctly optimized; nonetheless, an even better result was expected from the 2D analysis, a larger region of constant temperature at the inlet-outlet which would imply that the RHEX can get shrank but the opposite happened, even at steady state the RHEX hasn't attained thermal equilibrium at the inlet-outlet therefore it suggests that the RHEX needs to be longer.

Analysis

The following part summarizes some of the analysis performed on the selected RHEX. It is divided depending on the selected time domain. The steady state analysis is useful for determining how well the RHEX will perform once it is fully developed whereas the transient analysis would allow to know the performance at early stages. Besides, a brief comparison between the straight and wavy channel will be done to determine if there is a benefit to justify its inclusion.

Heat Transfer

Straight Channel

Steady State Heat Transfer

From the below image it can be noted that the heat transfer is completed until the inlet-outlet which suggests a correct sizing for the channel.

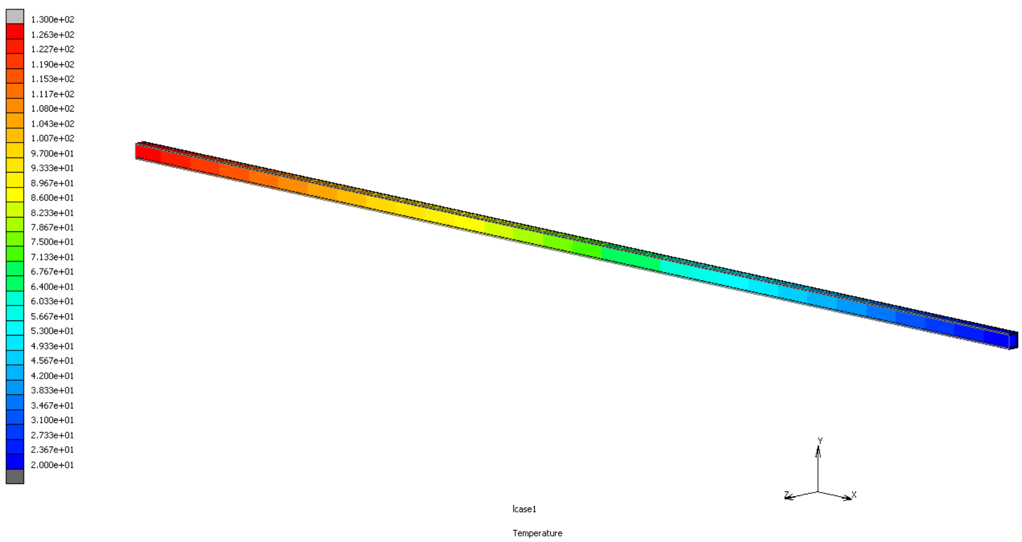

Figure 10. Temperature distribution along the channel (at z=0.0052m to visualize the profile at the middle).

In Figure 11, the change in temperature along the x axis is seen. The behavior shows a perfectly linear trend, this analysis implies that one could easily estimate the temperature at any point and even change the size of the RHEX if a higher or lower temperature is desired. For example, if the designer requires a RHEX at T_hot=130°*C* and T_cold=30°*C*, then with the help of this result the designer can estimate the required length using the same design constraints from the present work.

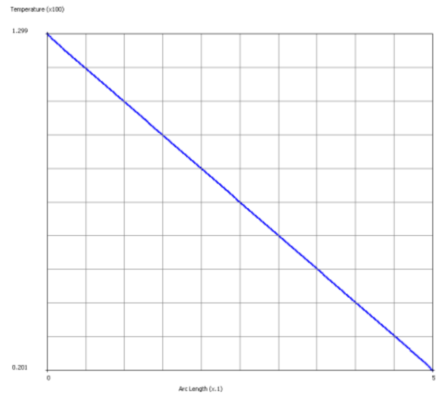

Figure 11. Temperature distribution along the X axis at the middle of the separting plate.

Transient State Heat Transfer

For the 3D transient analysis, it was practically impossible to solve. It can be seen in the image that for simulating 0.16 seconds it took slightly more than 14 hours. It was inviable to continue with the run due to external sources.

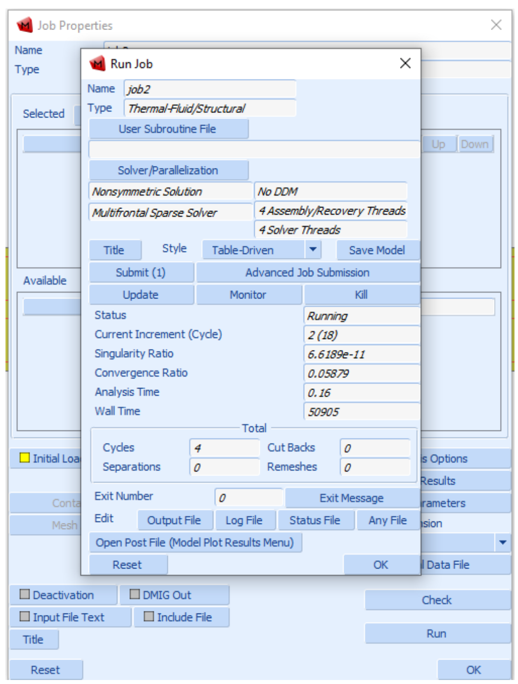

Figure 12. Transient state heat transfer run job information

The heat transfer from the hot channel towards the surroundings and cold channel is seen in figure 13. The heat starts penetrating the different mediums. The low thermal conductivity of the titanium is enabling the heat transfer to happen in such a way that the axial heat conduction phenomenon looks limited which is an explanation to the good heat transfer performance.

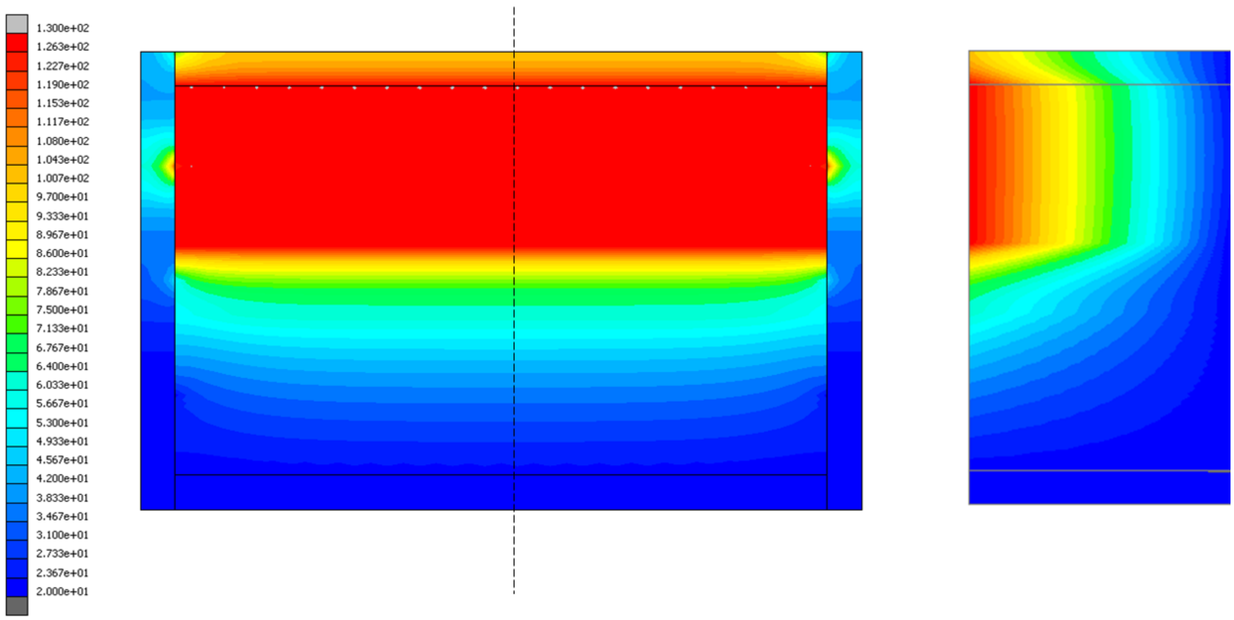

Figure 13. Temperature distribution of the hot inlet. Cross section (left), middle part (right).

To complement the transient analysis, the 2D model was run to see the propagation with time at slightly more time. In the figure, a different trend is seen at the same time (t=0.16 s). As it was seen in the validation section the 2D shows a slower, less penetrating heat transfer which now is confirmed with the help of these images.

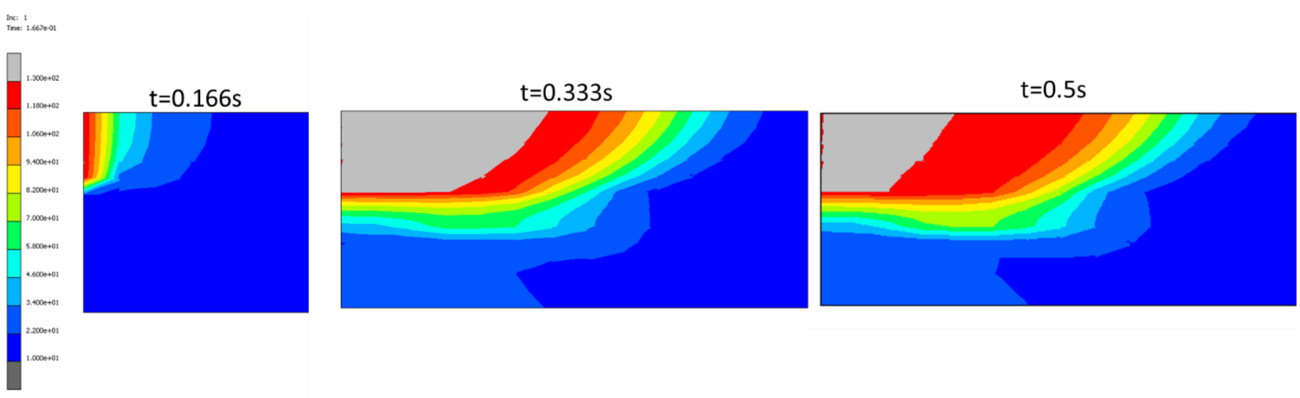

Figure 14. Heat propagation along x axis in 2D model.

Wavy Channel

Steady State Heat Transfer

To determine if the wavy channel brings up thermal advantages that might result in a smaller, lighter RHEX a brief comparison will be conducted. In figure 15, it is evident that the isothermal region close to the inlet-outlet of the channels is bigger for the wavy channel. This implies again that the wavy channel could be shorter effectively speaking because the extended length might still be larger than the straight channel. In other words, the wavy channel could occupy less space compared to the straight channel to transfer the same amount of heat.

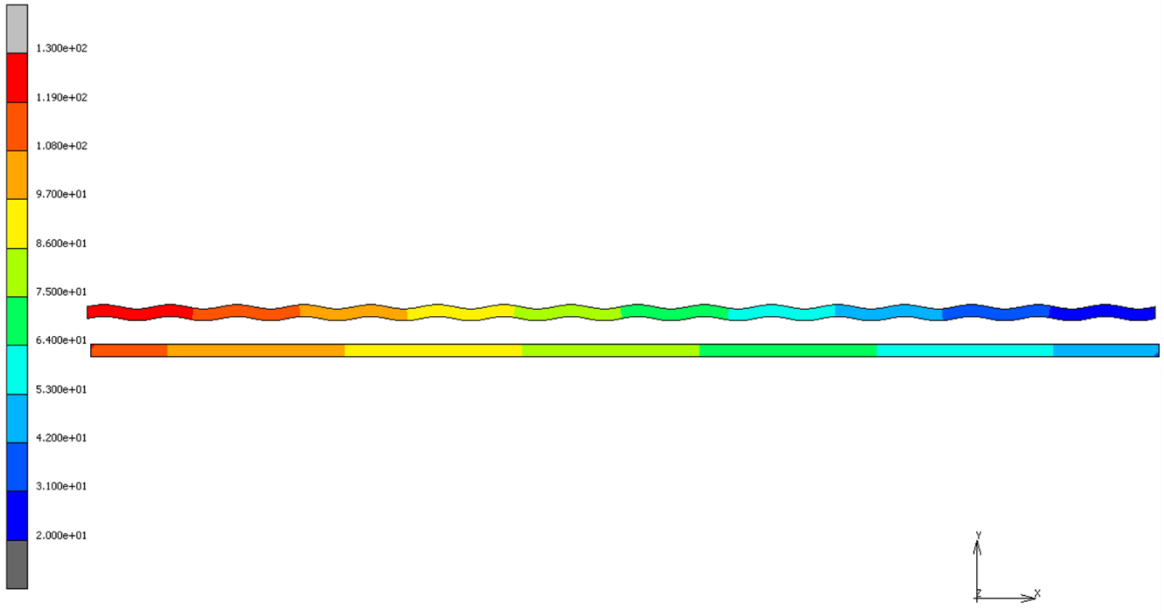

Figure 15. Comparison between the wavy and straight channel under the same parameters.

Transient State Heat Transfer

By comparing figure 14 and 15, there is no comparison between the two. The straight geometry shows a better heat transfer along the x axis compared to the wavy channel. Nonetheless, the wavy channel shows a better heat transfer along the y axis. This suggest that the heat is finding a more difficult path due to the waviness, possibly due the flow resistance that the waviness generates.

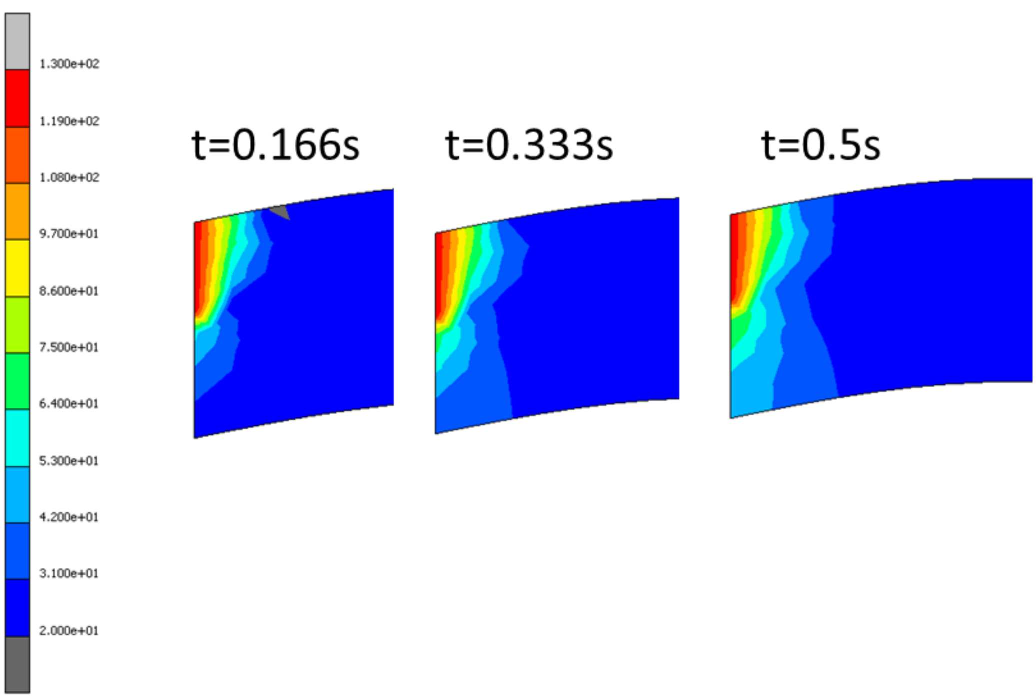

Figure 16. Heat propagation along x axis in 2D model for a wavy channel.

Additive Manufacturing

Straight Channel

Simulating the additive manufacturing for actual size of our RHEX would takes days on our PCs or computers available on campus. So, we are simulating only small part of the channel along the length.

To analysize additive manufacturing procedure, three dimensional printing of two layers of thickness 1μm each were simulated. The specimen was printed in lengthwise direction. The addtive manufacturing process generates transversely isotropic properties (properties in x & y is same but different in z) in the structure, hence two layer of manufacturing can give resonable information of whole channel. The additive manufacturing analysis was done based on lab08. So we will show the stress distribution (Comp 11, Comp 22, Comp 33), elastic strain components (Comp 11, Comp 22, Comp 33) and Von-Mises stress distribution. Since we can not include the GIF for the temperature contour, we will also include some pictures of temperture distribution of the specimen for different instance of time.

The temperture distribution over the surface at different time instant are shown in the figures below. Decipation of heat can be seen during the manufacturing process. By running 10s of different simulations, we found that the heat decipate faster if we use bigger baseplate which can also be explained thermodynamically. That is the reason we are unable to show temperature contour on the base.

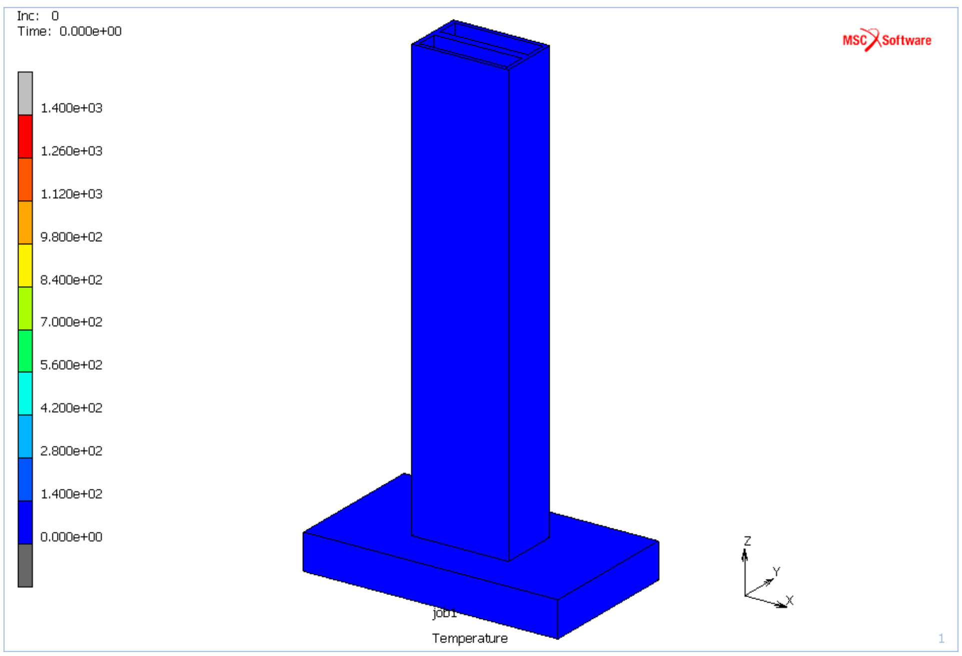

Figure 17. Temperature distribution at Inc:0 (at the beginning)

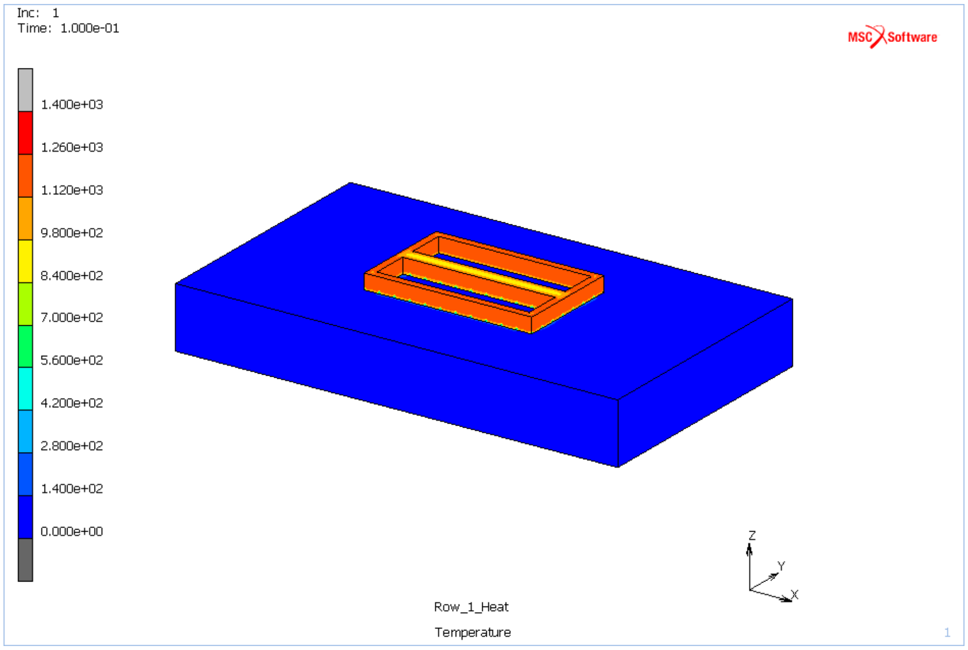

Figure 18. Temperature distribution at Inc: 1

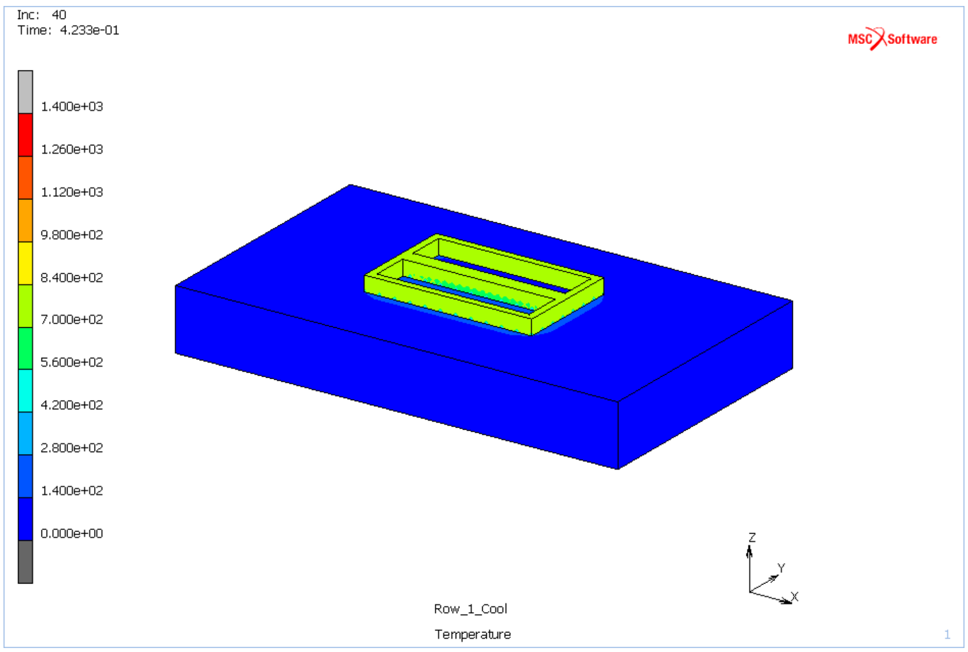

Figure 19. Temperature distribution at Inc: 40

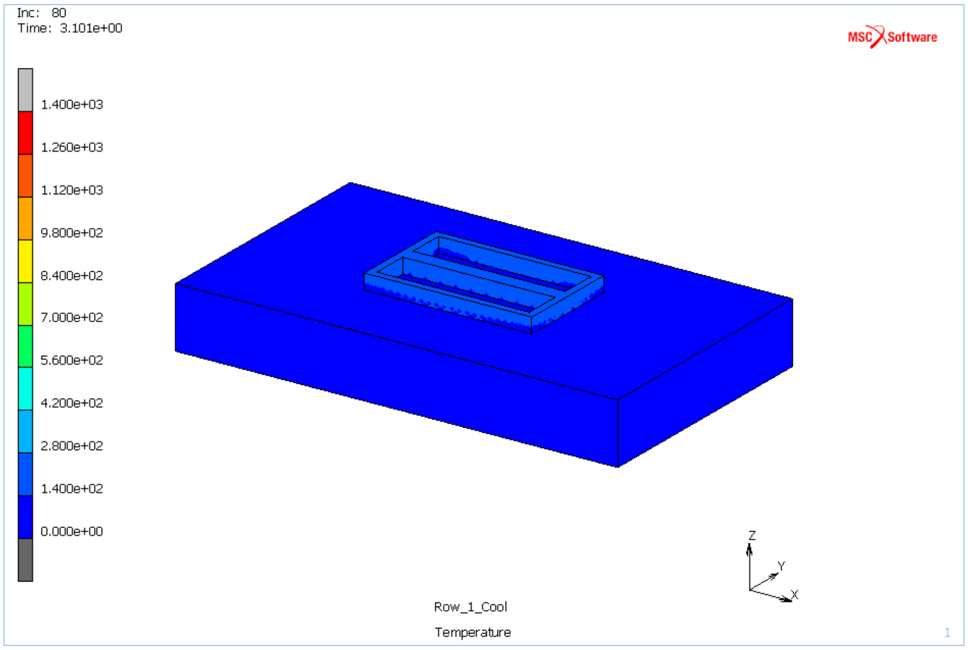

Figure 20. Temperature distribution at Inc: 80

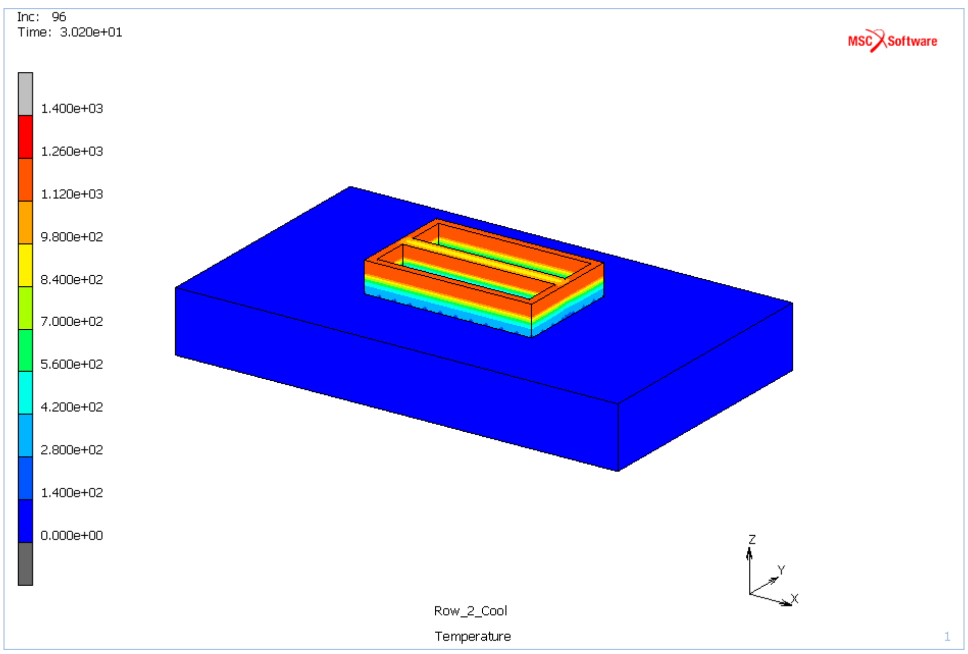

Figure 21. Temperature distribution at Inc: 96, when second segment was added

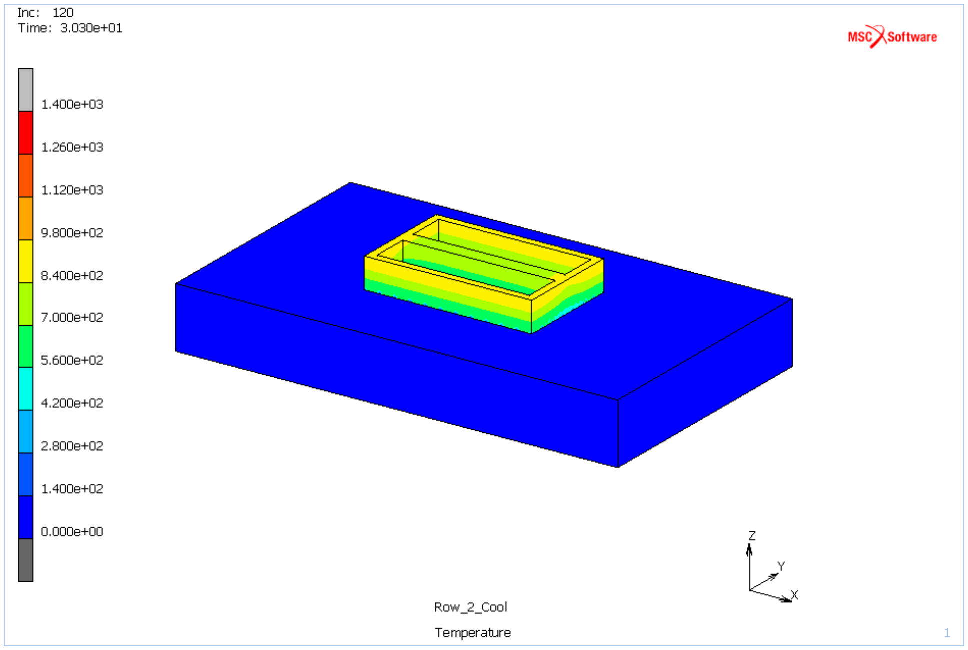

Figure 22. Temperature distribution at Inc: 120

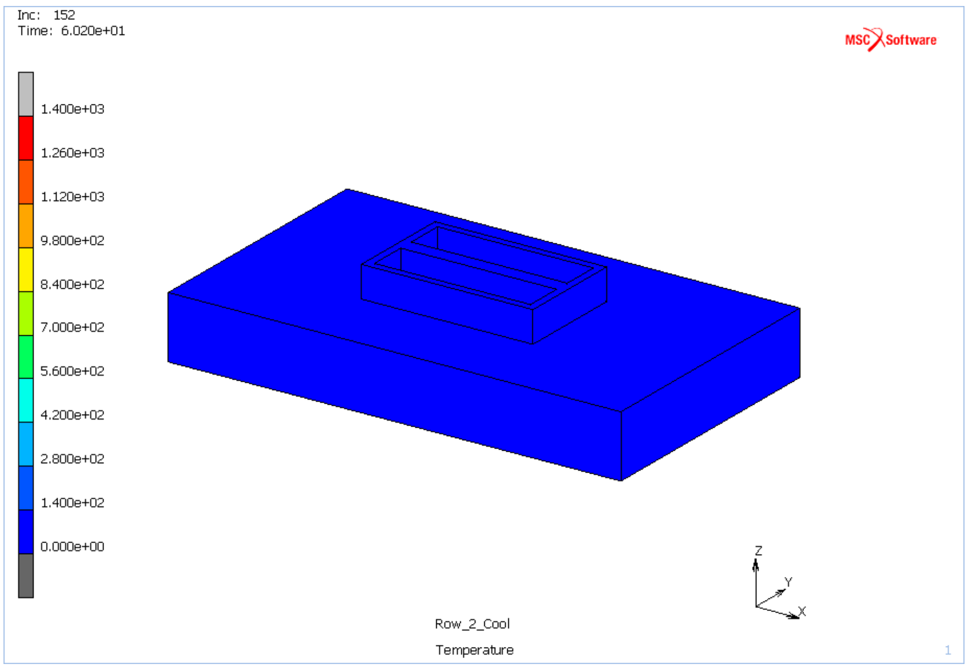

Figure 23. Temperature distribution at Inc: 152 (at the end of the simulation)

The stress distribution of internal section of the specimen shown in the figures below. To get the stress inside the channel, we used “toggle model clipping. Stress distribution of two instances is shown in each figure along with the toggle clipping position. At Inc: 70, stress (all 3 components) is in in light blue light green zone but at Inc: 140, it became greener indicating an increase in stress when another segment of specimen added on the top of first one.

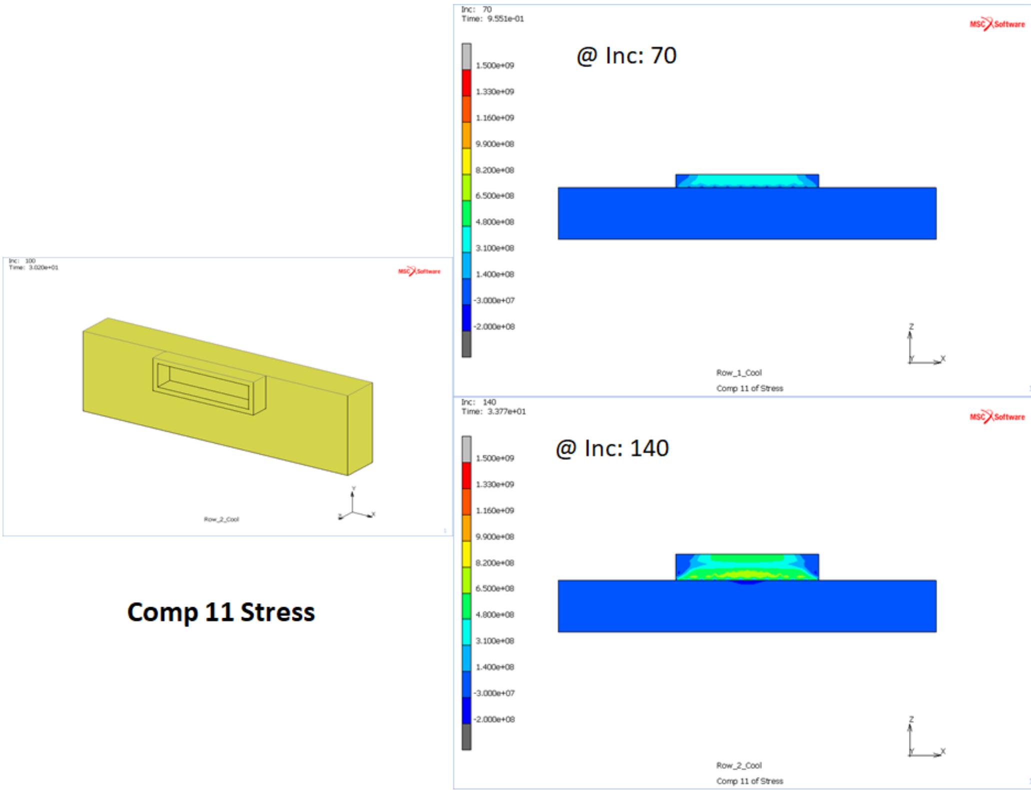

Figure 24. Stress component 11 (toggle clipping position is in between two channels along the width)

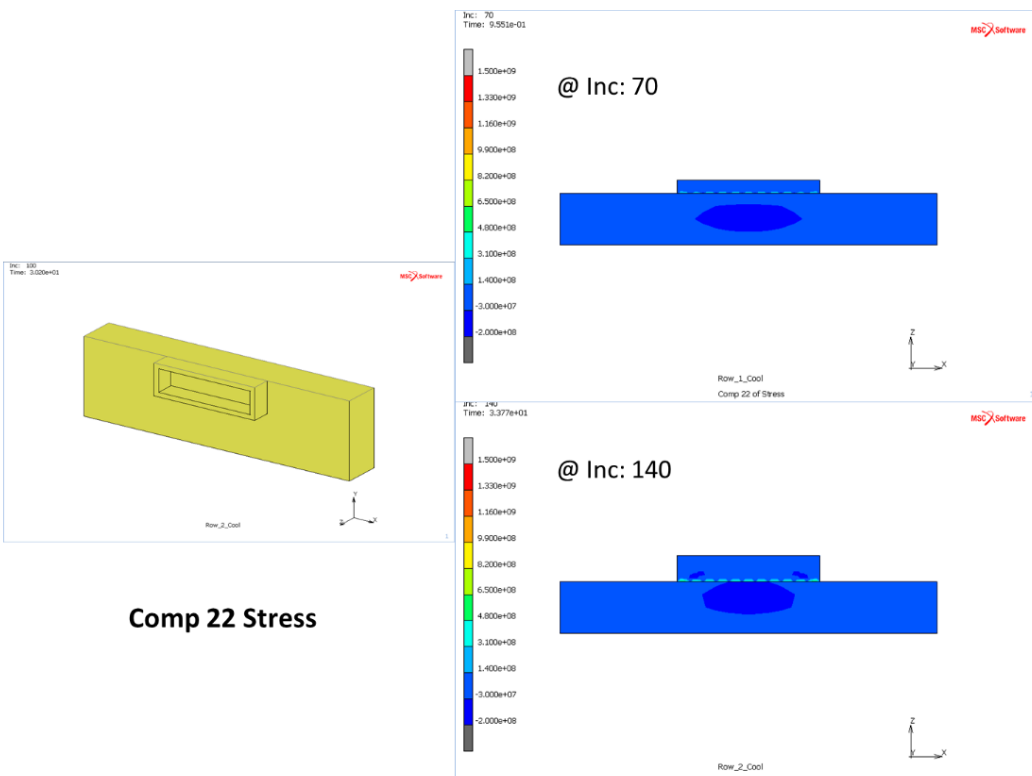

Figure 25. Stress component 22 (toggle clipping position is in between two channels along the width)

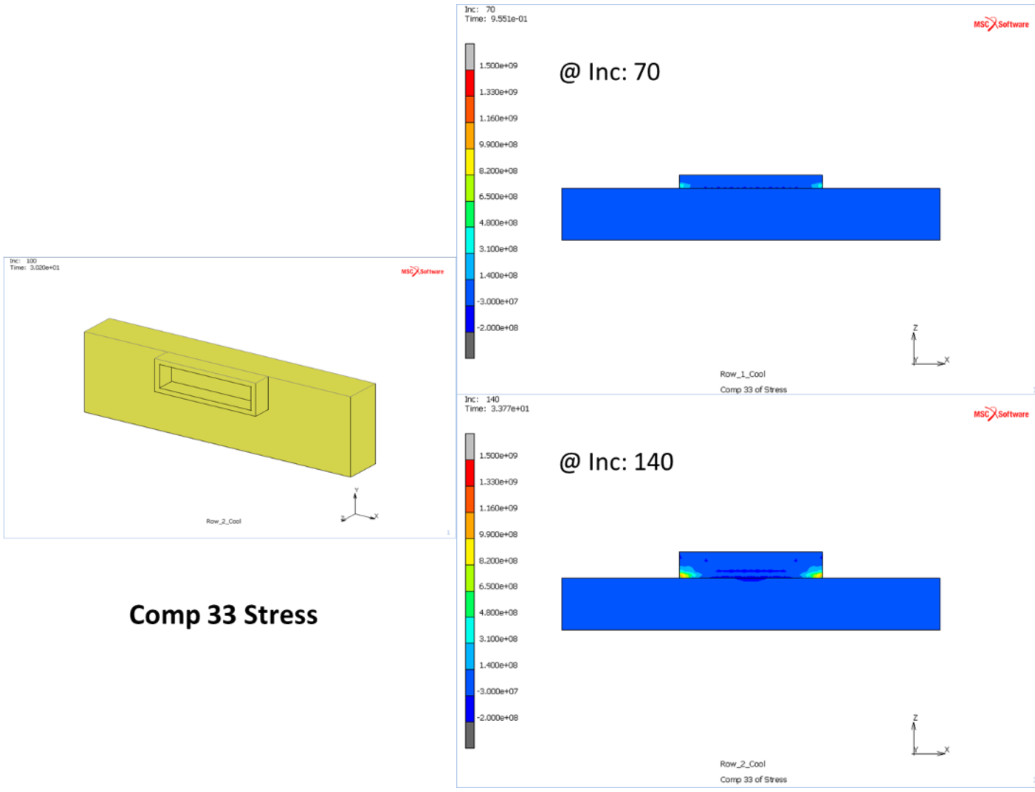

Figure 26. Stress component 33 (toggle clipping position is in between two channels along the width)

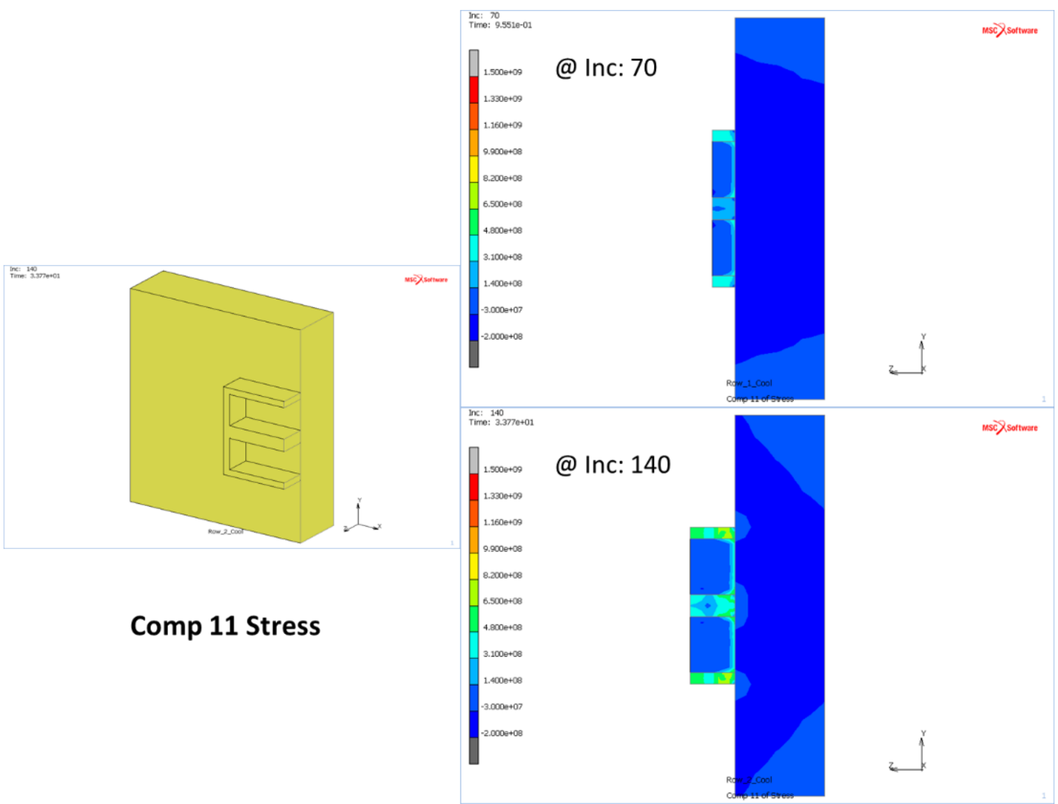

Figure 27. Stress component 11 (toggle clipping position is exactly middle of the channels)

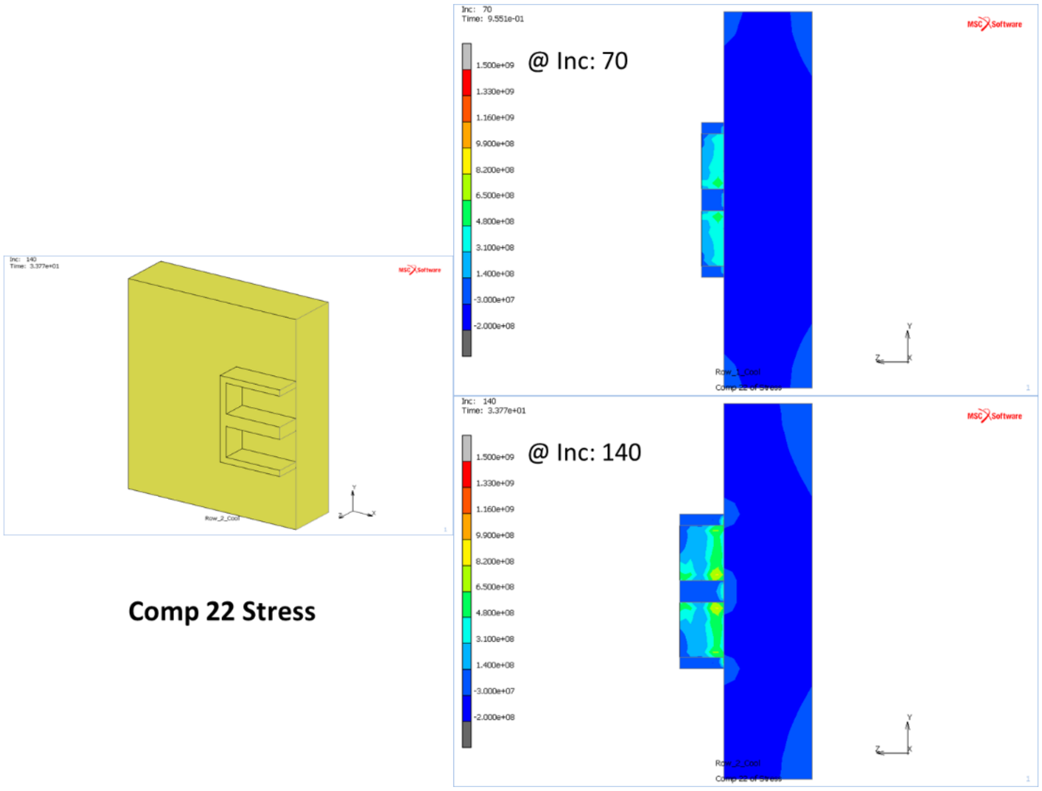

Figure 28. Stress component 22 (toggle clipping position is exactly middle of the channels)

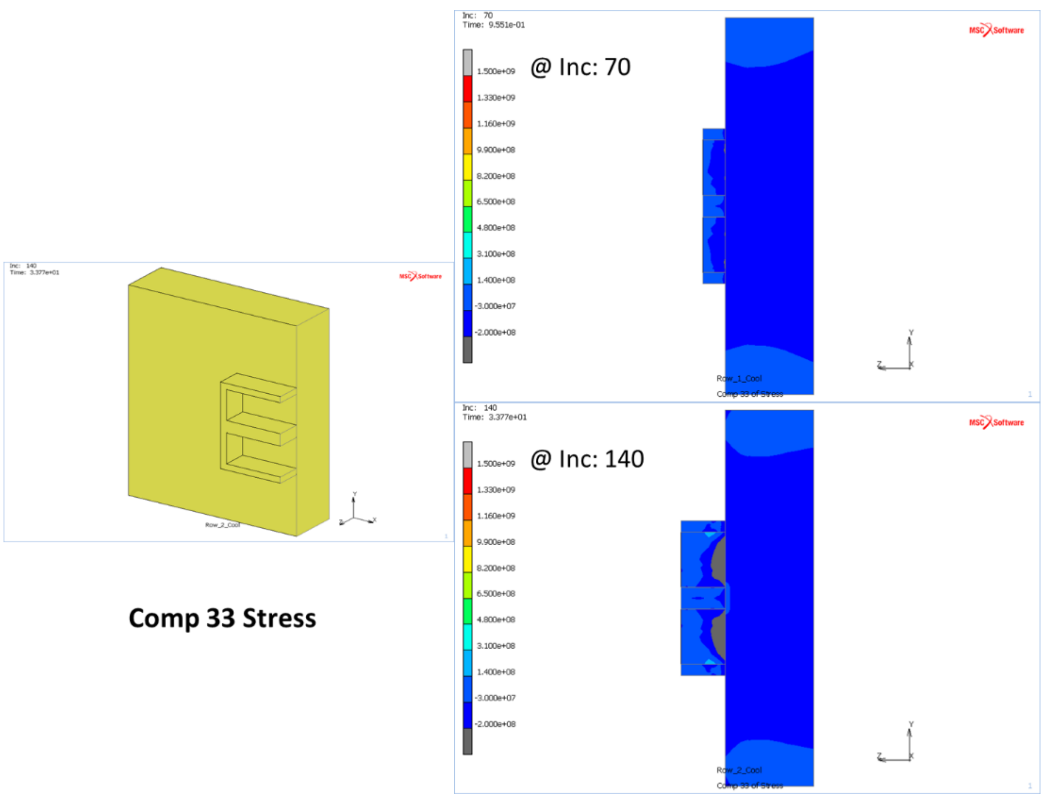

Figure 29. Stress component 33 (toggle clipping position is exactly middle of the channels)

The elastic strain distribution of internal section of the specimen shown in the figures below. To get the elastic strain distribution inside the channel, we used “toggle model clipping.

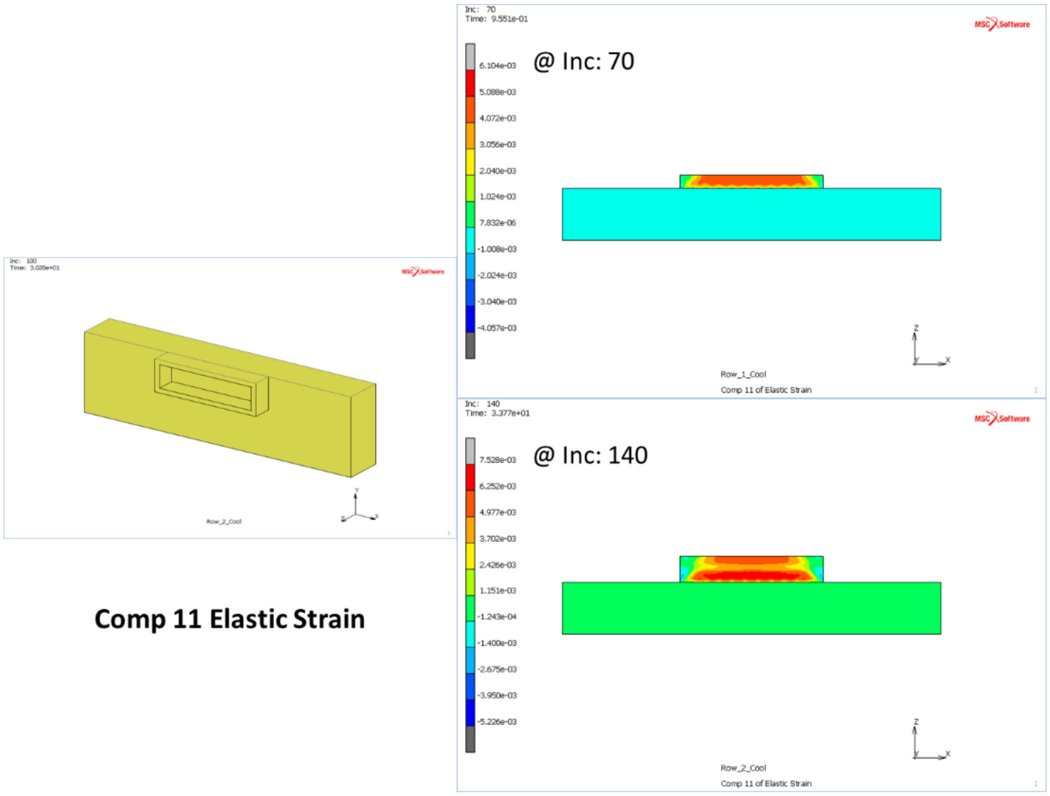

Figure 30. Elastic strain component 11 (toggle clipping position is in between two channels along the length)

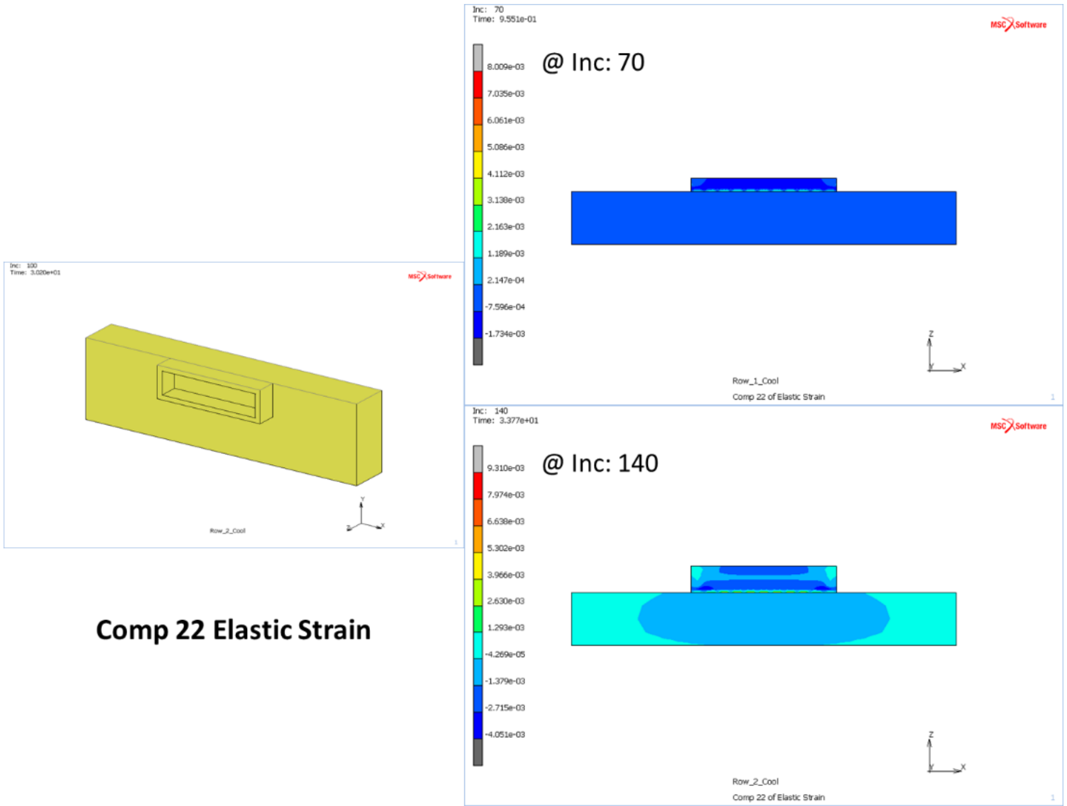

Figure 31. Elastic strain component 22 (toggle clipping position is in between two channels along the length)

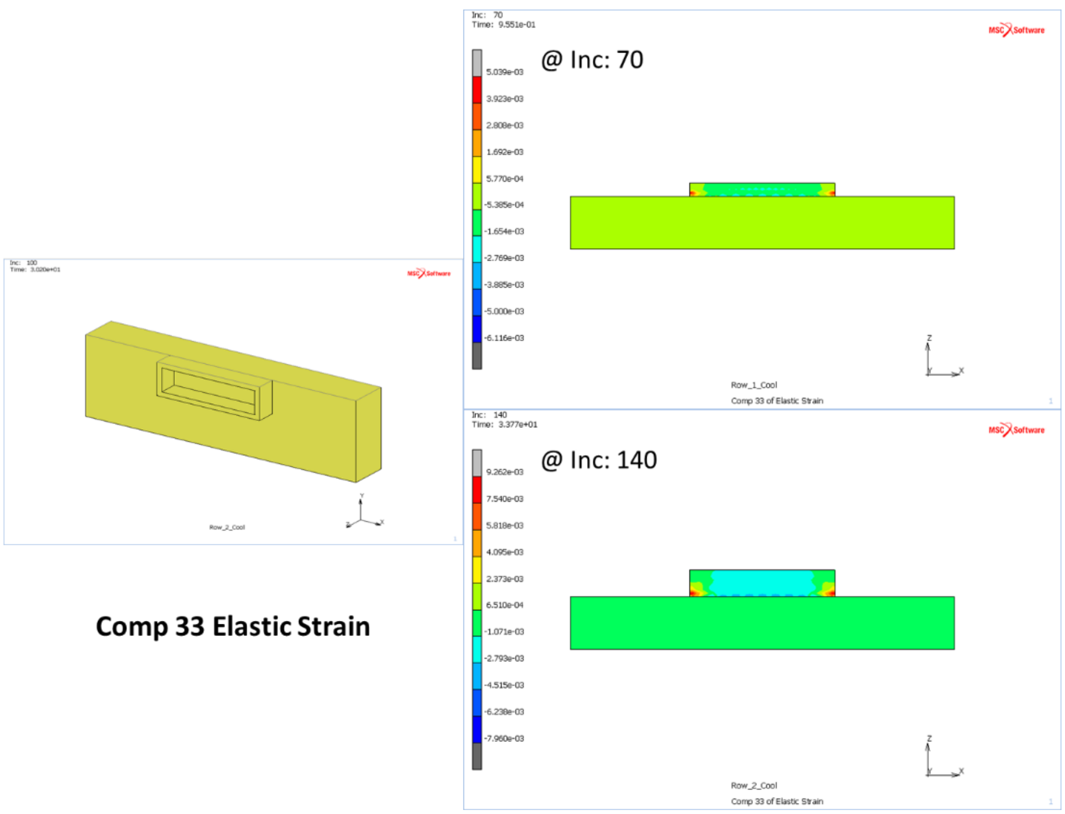

Figure 32. Elastic strain component 33 (toggle clipping position is in between two channels along the length)

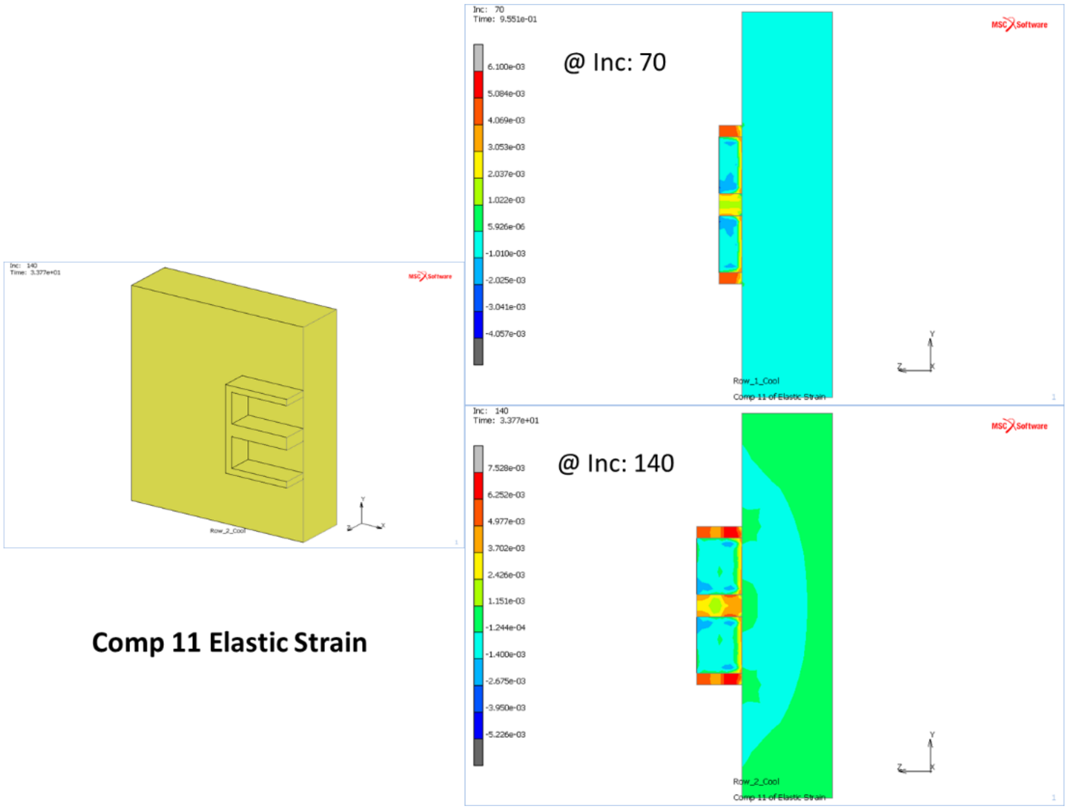

Figure 33. Elastic strain component 11 (toggle clipping position is exactly middle of the channels)

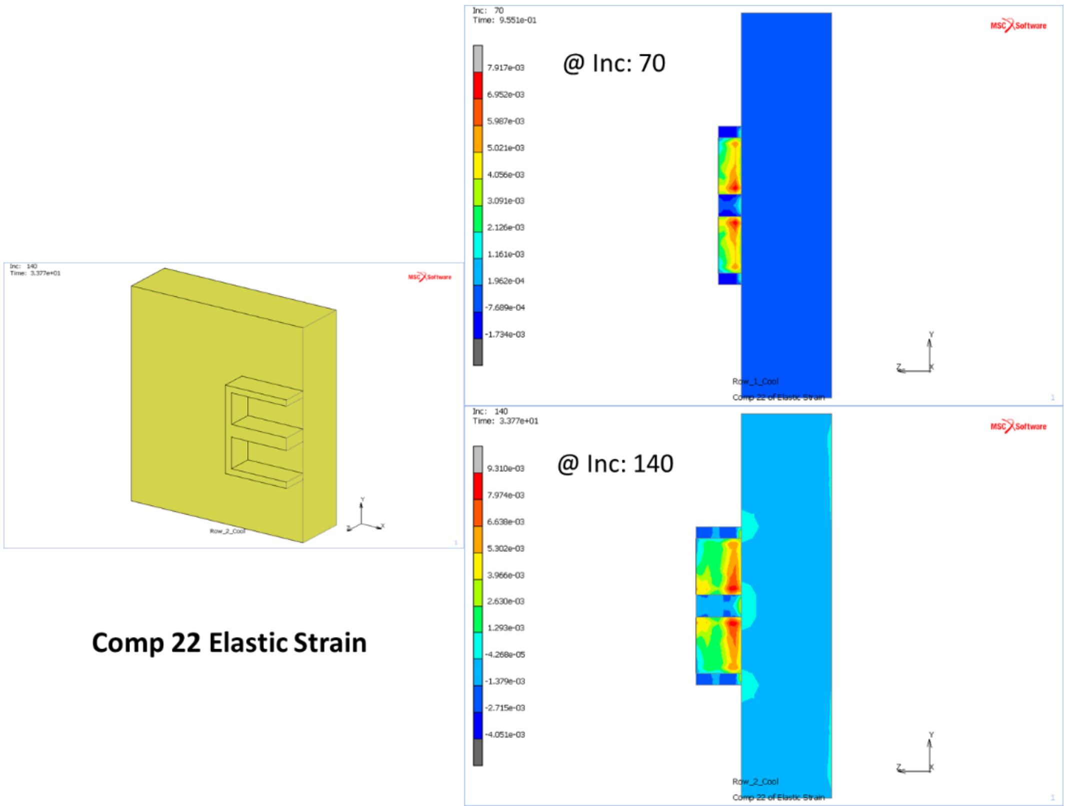

Figure 34. Elastic strain component 22 (toggle clipping position is exactly middle of the channels)

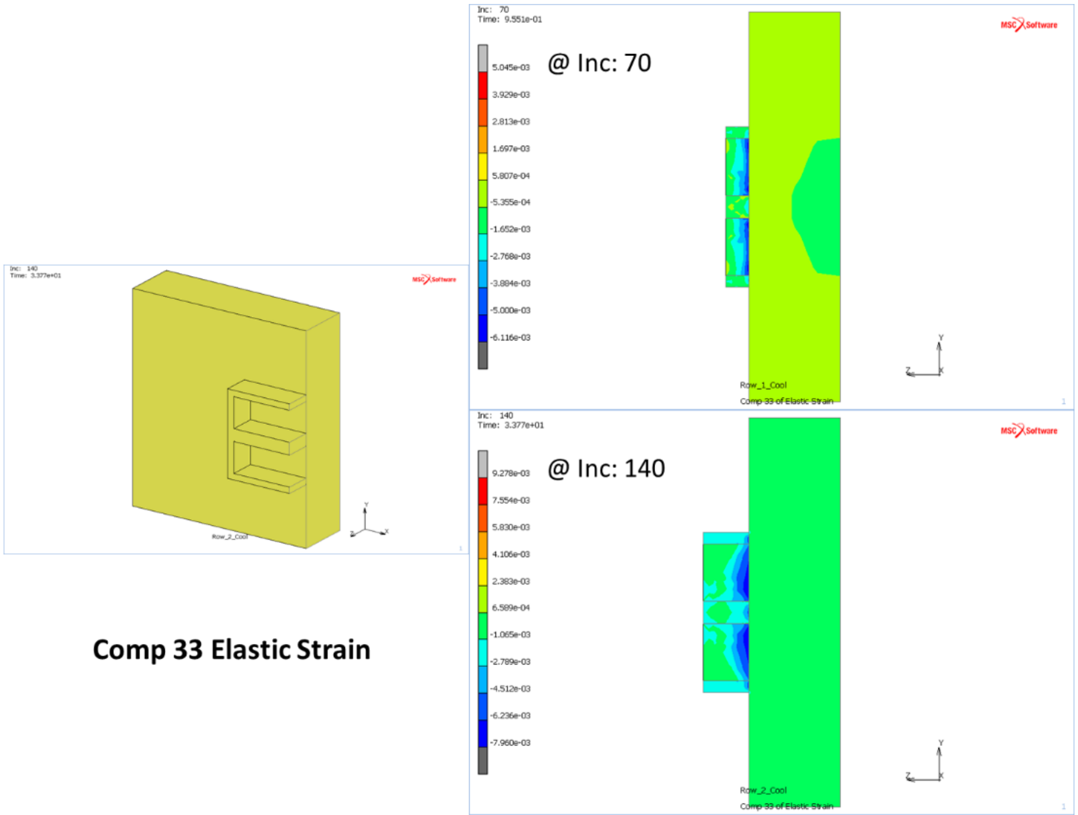

Figure 35. Elastic strain component 33 (toggle clipping position is exactly middle of the channels)

Von Mises stress is a value used to determine if a given material will yield or fracture. It is mostly used for ductile materials, such as metals. The von Mises yield criterion states that if the von Mises stress of a material under load is equal or greater than the yield limit of the same material under simple tension then the material will yield. Von Mises stress is considered to be a safe haven for design engineers. Using this information an engineer can say his design will fail, if the maximum value of Von Mises stress induced in the material is more than strength of the material. The Equivalent Von-Mises stress distribution of specimen at different instances of time are shown in the following figures.

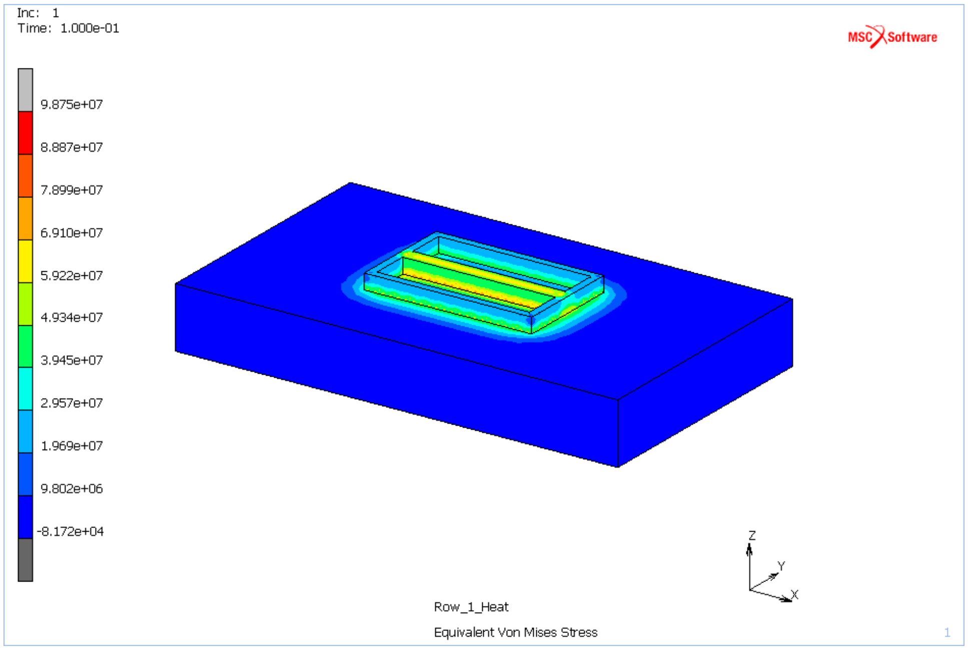

Figure 36. Von-Mises stress distribution at Inc: 1

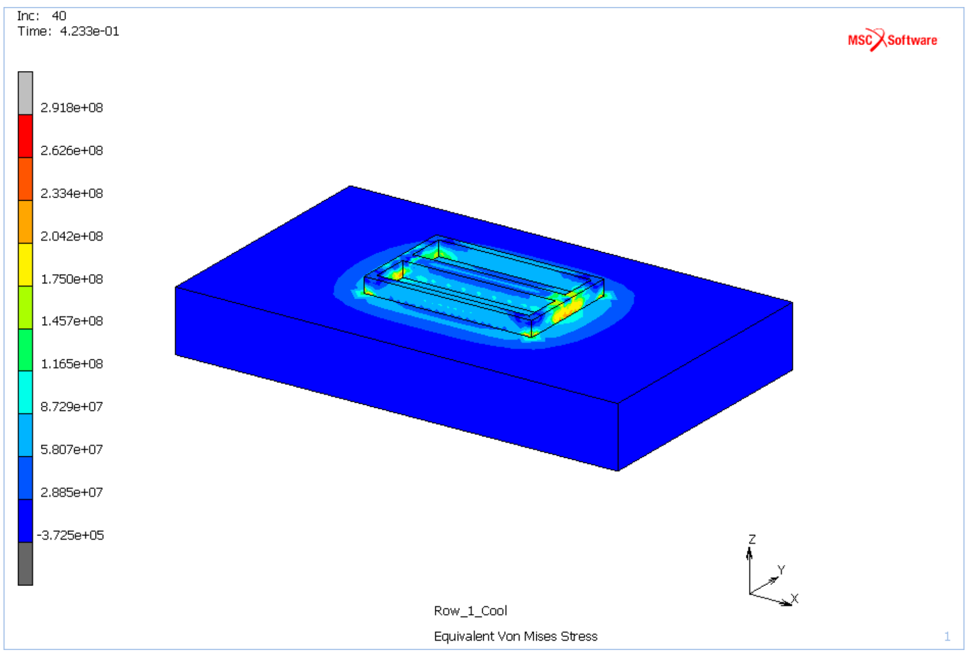

Figure 37. Von-Mises stress distribution at Inc: 40

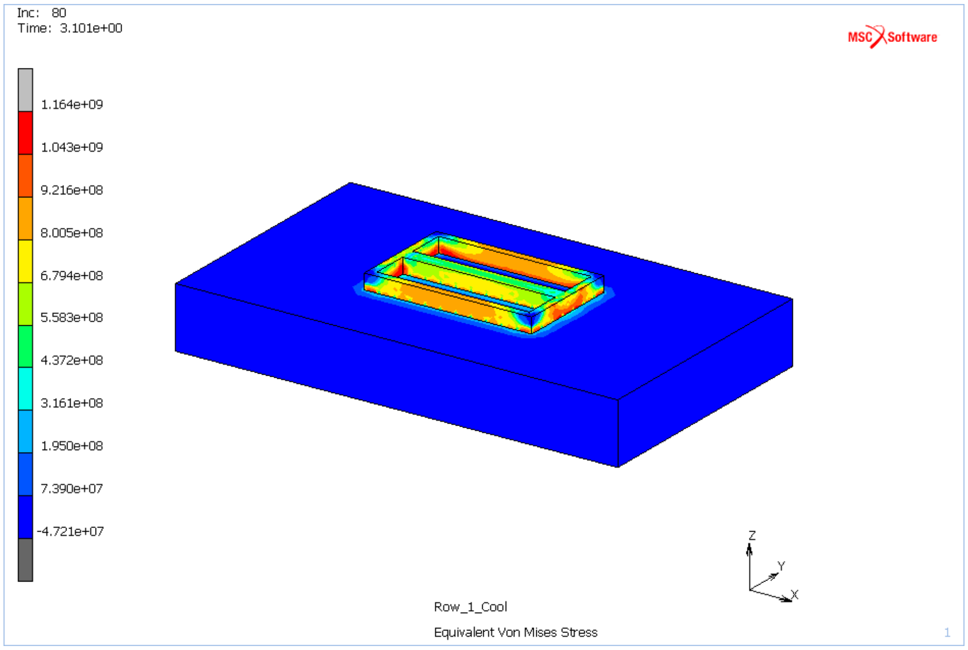

Figure 38. Von-Mises stress distribution at Inc: 80

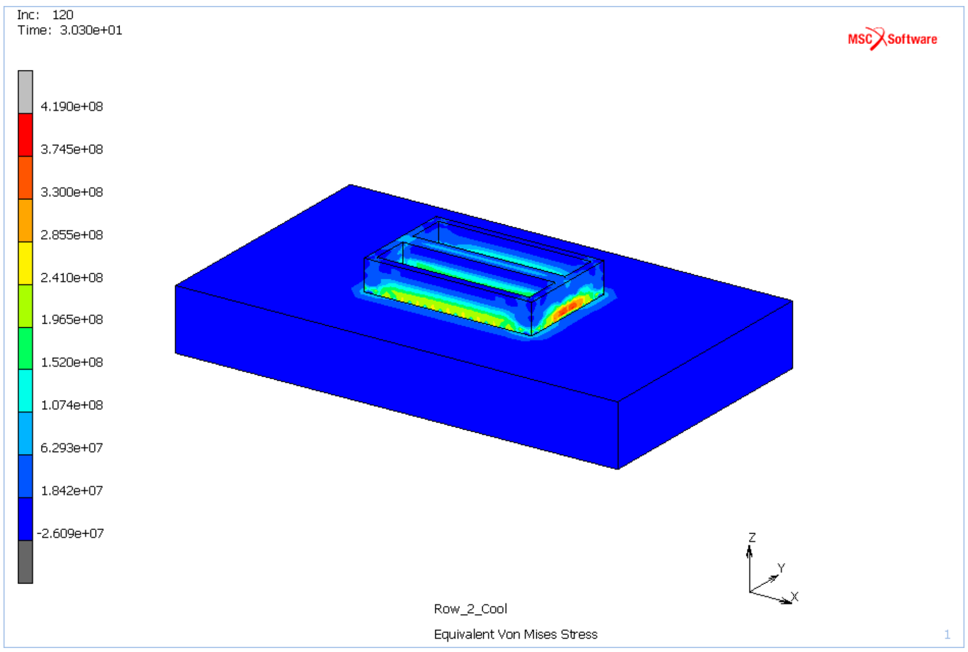

Figure 39. Von-Mises stress distribution at Inc: 120

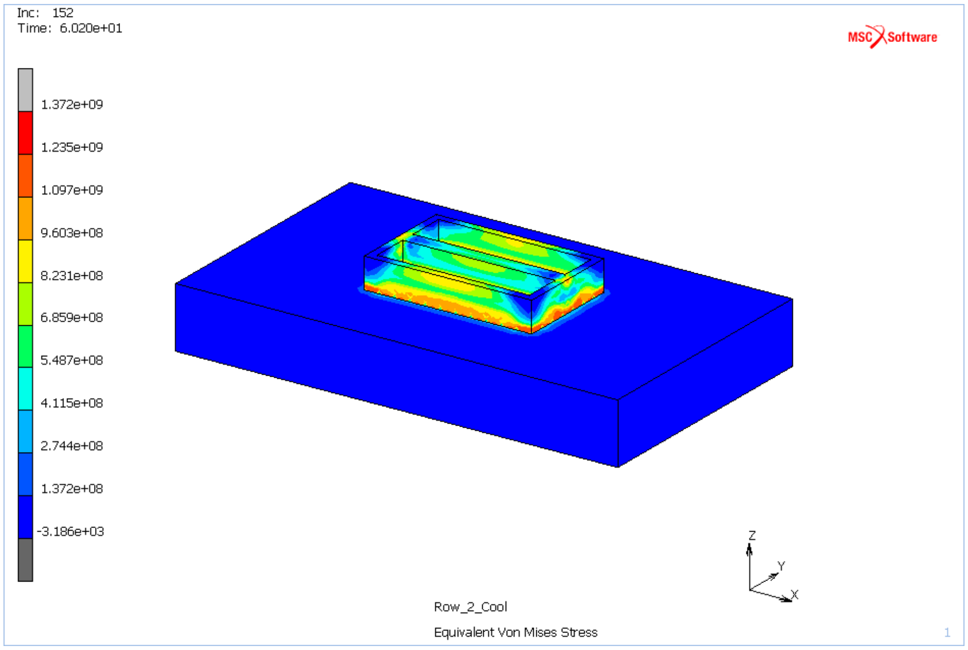

Figure 40. Von-Mises stress distribution at Inc: 152 (at the end)

Conclusions

Based on the obtained results, the waviness does allow to reduce the effective length of the RHEX but not necessarily because the heat transfer performance is enhanced, it could be just because the extended length is the same or even bigger than the length of the straight channel.

The results are not entirely reliable given that the 2D analysis showed lower results compared with the 3D; nonetheless, the comparison between 2D models at the same times is more reliable. Both 2D models were done under the same parameters and boundary conditions, therefore even if they are not highly accurate, the trends should be correct.

The transient analysis ended up being impossible to run in 3D due the immense number of elements required. The geometry of RHEX presents difficulties for this type of analysis because it cannot be cut or assumed to be shorter, it must be analyzed entirely. The present model was just for a pair of channels but in reality RHEX have even thousands of channels therefore it can be said that currently it is unviable to conduct transient analysis on a entire RHEX.

The current results served to somewhat validate the code that is being developed however it served as well to show strong deficiencies in the structural consideration. According to the software the structure would not withstand the prescribed pressure differences.

Marc Mentat (MSC) software showed to be powerful on the structure and heat transfer sides, though, its fluid analysis package is very limited, and this makes the software not ideal for analyzing systems such as the RHEX. This is also a source of error that for now, cannot be quantified. The idea/implementation of waviness into RHEX is attractive because it induces a shifting of the velocity profile towards the separating plate, and it seems that MSC lacks this detailed solution. Being able to solve for local deflection and determining how that would influence the pressure drop an eventually all the phenomena is crucial.

The AM analysis ended up being of great interest, the near future of RHEX will be dictated by the AM limitations and it is triggering a new “revolution” as the designers can come up with unreally complex geometries. Understanding how the AM would generate a distortion into the part will be useful while manufacturing future parts.

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