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Study of Heat Exchangers in Small Modular Reactors (SMRs)

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Abstract: This paper presents a comparative study of different coolants, materials, and temperatures that can affect the effectiveness of heat exchangers that are used in small modular reactors. The corrugated plate heat exchangers were chosen out of different plate options for testing purposes because of their ease of access and better performance than other existing heat exchangers in recent years. SolidWorks enables us to see various results between water coolants and helium coolants acting upon different types of conducting metals, which were selected from different fluids that ultimately satisfied accessibility requirements and were compatible with the software. Though not every element, material, fluid, or method was used in the testing phase, their purpose is to help further research that is to come since the innovation of nuclear power is the future. The tests that were performed are to help better understand the constant necessities that are seen in heat exchangers and through every adjustment see what the breaking points or improvements in the machine are. Depending on consumers and researchers, the results may give further feedback as to show why different types of materials and fluids would be preferred and why it is necessary to keep failures to improve future research.

Keywords: Heat Exchangers, Solid Works, Coolants, Small Modular Reactors, Nuclear Power, Nanofluids, Nusselt Number, Friction Factor, Reynolds Number

1. Introduction

Nuclear reactors have been in production since the 1900s, which have been a major contributor to the U.S. and have innovated tremendously since then. The next improvement for nuclear reactors was the sizing of the reactor itself since the sizing of large nuclear reactors has caused problems in the past such as Fukushima and Chornobyl and because of them have made changes in regulation [8]. Small modular reactors are an improvement of large nuclear reactors since the sizing and power are reduced while at the same time meaning that multiple reactors can be in the same plant and if there were to be a leak or incident then the other reactors can still be active. With this being a newer concept of reactors, there are many ways to cool down and keep small modular reactors operational, creating a conflict in finding the most efficient external cooling method [3].

Heat exchangers are the external cooling method that keeps the fluids in the reactor at a consistent range of temperature to not cause overheating, this allows for consumers to have more time in operation. When a reactor is in operation, the fluid being circulated needs to be cooled down before overheating, which introduces the need for a heat exchanger. This serves the purpose of recirculating the fluid into a more stable temperature causing it to be integrated back into the reactor which can be reused. Different variations of heat exchangers have been made in recent years with their own advantages and disadvantages including the shell and tube, passive residual, gas-cooled pebble bed, and plate heat exchangers [9]. The reason for using a plate heat exchanger instead of the other examples can be because the shell and tube will halt production due to long periods of maintenance, passive residual heat exchangers are in a closed loop with lesser amounts of no compressible gas being produced which causes more condensation of unusable fluid [5]. With the gas-cooled pebble bed having temperatures reaching 900 degrees Celsius or more, it could be difficult to find cost-effective materials that can withstand that temperature.

Out of all the analyzed heat exchangers, conclusions were made that the plate heat exchanger is more efficient because of its production rate, ease of access to gaskets and plates, and the material being cost-effective. A plate heat exchanger comprises plates, gaskets, sealant plates, and rods containing the device [1]. It has an inlet and outlet that allows cold and hot fluids to interflow without combining which causes the thermodynamic properties to become exchangeable through a conducting plate stabilizing the temperature within that is then redirected back to the reactor. There are variations when it comes to plated heat exchangers and the variation that is a promising innovation has been the corrugated heat exchanger, with there being indentions of different angles to manipulate the flow of the fluid and making the material thinner in areas to easily exchange the different temperatures. Figure 1 shows a finished product of a fully constructed corrugated plate heat exchanger which can be implemented for small modular reactors and other commercial needs.

Figure 1. *Example of corrugated plate heat exchanger [6].*

2. Materials and Methods

2.1. Materials

All materials that were used and theorized with are shown on table 1 below, the price per kilogram is in American dollars and the melting temperature is in Celsius, this is shown to clarify everything used throughout the research.

Table 1. *Prices and melting points from each material.*

Material	Cost/kg ($)	Melting Temp (Celsius)
Silicon Carbide [13]	0.90	2730
Aluminum [11]	2.39	660
Titanium [16]	10.50	1668
Copper [12]	7.28	1085
Alloy 617 [15]	30	1332
Teflon [14, 17]	14	327

2.2. Structure of the Plate Heat Exchanger

The software that was used for experimentation and results is Solidworks (2021) recreating a model using measurements from previous articles [4], experimental data, and available materials. Corrugated plates were the constant variable when it came to the experimental data since the materials and fluids changed to test the differences and effectiveness of the different elements, the plate had corrugations at 60 degrees based on the middle. Aluminum, Copper, Titanium, and Alloy 617 were used to test the endurance of temperature, stress, and heat conductivity while the sealants that were used to seal the liquid in were Teflon and Silicon Carbide. Partial portions can be seen of the corrugated plates in Figure 2 which shows the dimensions and indentions of the corrugated plate in millimeters, the thickness of the plate is 3 mm, the indentions of the corrugations are 2 mm and the outdent measurement are 1 mm. The plate itself uses arrow-shaped corrugations to guide the fluid in the direction of the following outlet and to make portions of the plate thinner to allow more efficient heat transfer possible.

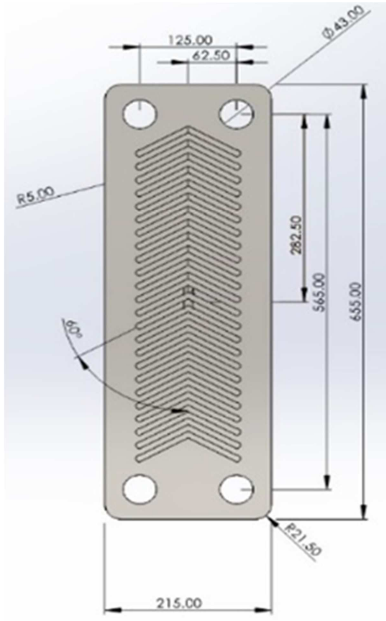


Figure 2. *Corrugated plate.*

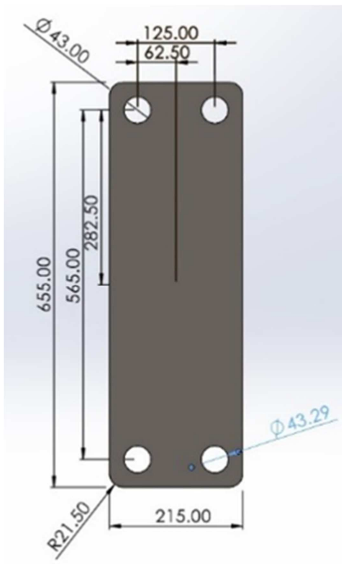


Figure 3. *Front and back plate.*

The front and the back plate share many similarities when it comes to measurements that are in the normal corrugated plates apart from no indentions and outdents, the purpose of the front and back plates shown in Figure 3 is to contain the fluid being used and make sure that the seal remains intact by being a flat surface.

The gaskets as shown in Figure 4 are reversed after every plate and the purpose of them is to seal in the fluid to make sure that none of it seeps out either from excessive pressure or temperature. There were two types of materials that were tested for the gaskets that were Teflon, a very common type of rubber that could not withstand higher temperatures than further tests required, and Silicon Carbide, which proved to be resilient when it came to withstanding higher amounts of temperatures.

Figure 4. *Gaskets.*

2.3. Finalizing Testing Model

By uniting all previous figures, Figure 5 is constructed which includes: 16 corrugated plates, a front and back plate, and 17 gaskets with every other gasket being reversed to allow the fluids (hot and cold) to interflow without mixing. The overall function of the model that was theoretically designed serves the purpose of finding a suitable heat exchanger with tests to decide how many variables need or had to be changed to improve theorized ideas and concepts. With constant improvements, the materials and fluids were constantly changed to improve the model itself which can be useful for further and future research to see what functionality can be obtained from each element [10].

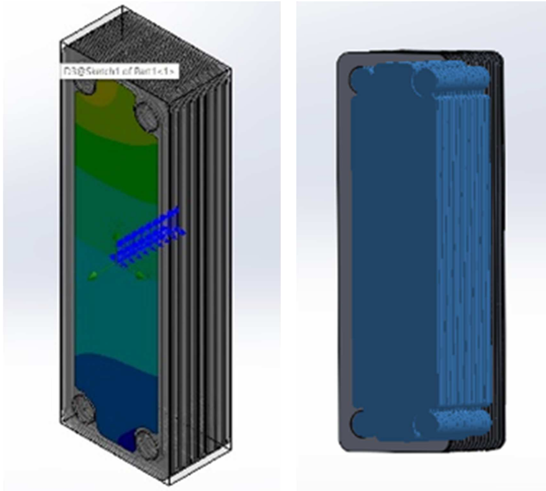


Figure 5. *Finished experimental model.*

2.4. Analyzing Theoretical Fluids

Figure 6 shows the thermal performance of various fluids including Water, Titanium Dioxide, Beryllium Oxide, Copper Oxide, and Zinc Oxide. The titanium had better results in regard to nanofluids compared to other materials in this previous study. Nusselt number is a dimensionless parameter used in calculations of heat transfer between a moving fluid and a solid body. The Nusselt number increases with the Reynolds number. It is attributed to the increase of turbulent intensity as the Reynolds number increases, leading to an amplification of convective heat transfer. [2]

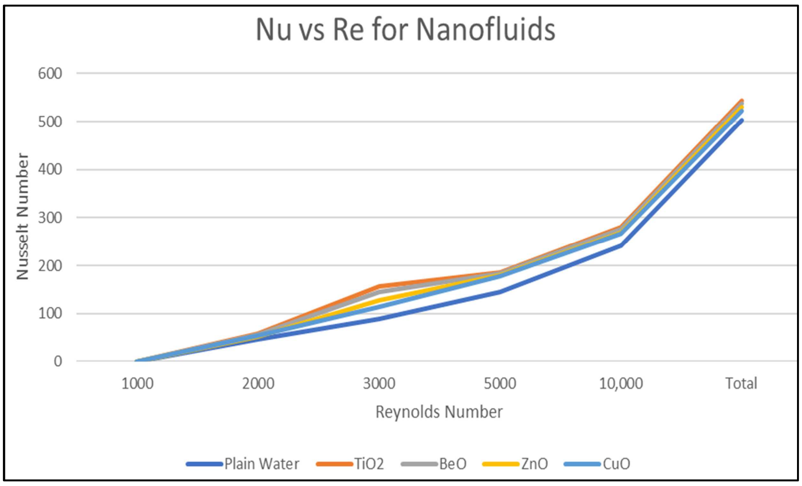


Figure 6. *Nusset number vs reynold number for nanofluids.*

The friction factor in Figure 7, shows that plain water had the highest friction factor at a flow of 2000 in Reynolds number, which helps better understand the effectiveness of different nanofluids.

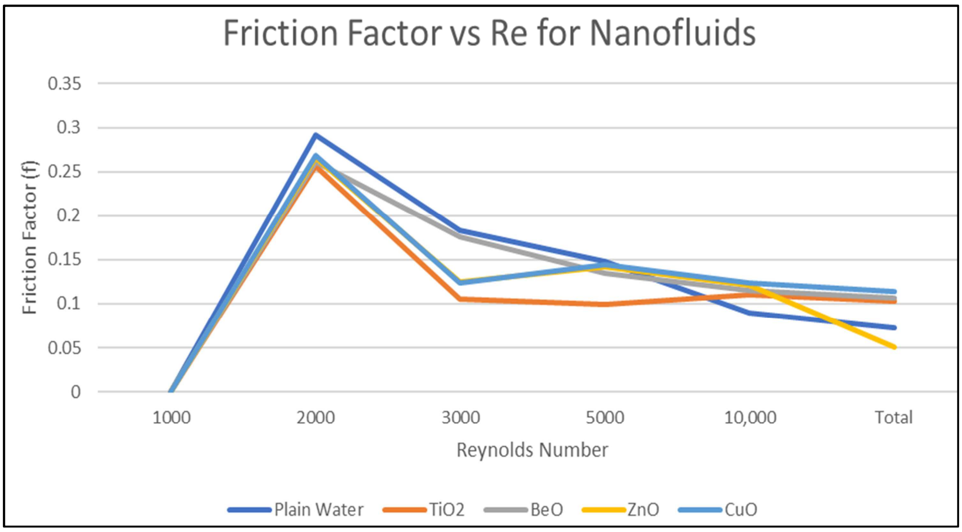


Figure 7. *Friction factor vs reynolds number for nanofluids.*

Shown in Figure 8 are the Reynolds number and thermal performance factor with the four previously stated materials excluding water. Titanium dioxide has the higher thermal performance factor while Copper Oxide has the lowest. The reason titanium dioxide had better performance is due to its thermal properties having high heat resistance. Compared to other liquids, titanium dioxide has better heat transfer characteristics.

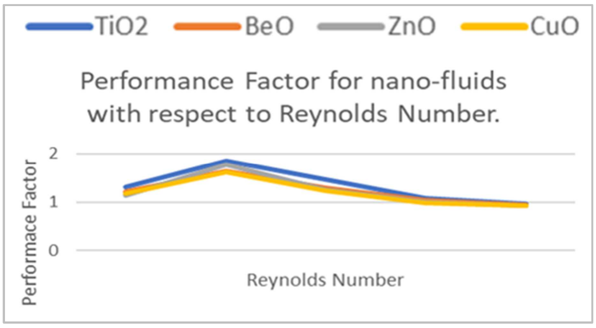


Figure 8. *Performance factor for nano-fluids with respect to reynolds number.*

Although ultimately the only two fluids that were tested were water and helium it is still useful to know information about other fluids that could prove to be useful for further research that was not able to be used through SolidWorks.

3. Results and Discussion

Implementation of all theoretical and investigative analysis helps to show where all the different tests and results come from, although not every fluid was used throughout the tests the two fluids that were used were water and helium, which have both been used in previously known small modular reactors. In this section there will be tests shown through figures that are in order of when they occurred, the main colors used were: orange, red, and green. Orange represents the Logarithmic Mean Temperature Difference (LMTD) which was not used heavily since it gave different inconsistent results. Red represents the average temperature of the cold fluid, depending on if it is in the water section of testing or the helium section, from the moment it enters to where it averages to. Green represents the average temperature of the hot fluid, depending on if it is in the water section of testing or the helium section, that enters the heat exchanger and the temperature that it averages throughout the cycles. On the x-axis, there is the cycle number that it is currently generating and, on the y-axis, it shows the temperature of the corresponding hot or cold fluid.

3.1. Results When Water Is the Coolant

Water contains dissolved ions which allow it to conduct heat, it has a high specific heat capacity allowing it to absorb copious amounts of heat without increasing the temperature and it is easily accessible to many regions, making it a good fluid to perform tests on. All the temperatures chosen for testing in the following experiments were chosen from a previous article [7]. The log means temperature difference (LMTD) can be disregarded since it gives a negative averaged value.

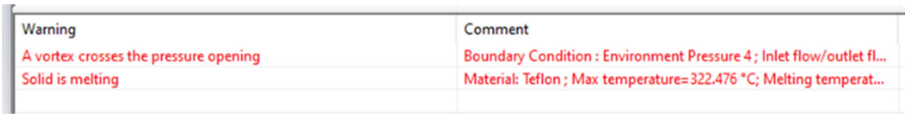
The materials used in this test as shown in Figure 9 were Aluminum plates and Teflon gaskets. The inlet temperature was set to 100 C, the outlet temperature was set to 20 C and the velocity was 0.1 m/s. The test was successful in how it was able to complete a cycle and lower the temperature of the 100 C water.

List of Goals

Name	Current Value	Progress	Criterion	Averaged Value
LMTD	0 °C	Achieved (IT = 99)	8998.66 °C	-1.7053e-13 °C
SG Average Temperature (coldwater) 1	67.6624 °C	Achieved (IT = 118)	1.45233 °C	68.1192 °C
SG Average Temperature (hotwater) 2	53.9034 °C	Achieved (IT = 127)	1.39485 °C	53.8336 °C

Figure 9. *Test 1.*

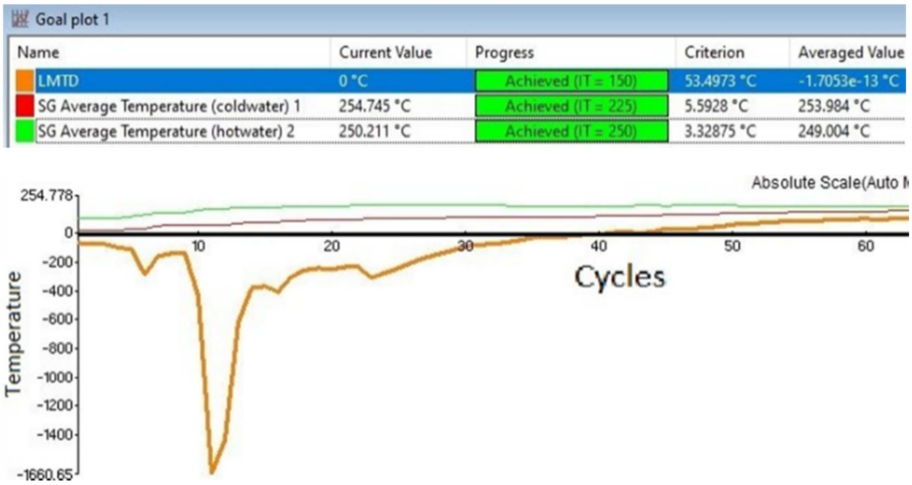
The materials stayed the same as in test 1 with only the water being increased to 323 C for the inlet temperature and 200 C for the outlet. The test was unsuccessful because the Teflon gaskets could not withstand the high heat of the inlet temperature as shown in Figure 10.



Warning	Comment
A vortex crosses the pressure opening	Boundary Condition : Environment Pressure 4 ; Inlet flow/outlet fl...
Solid is melting	Material: Teflon ; Max temperature=322.476 °C; Melting temperat...

Figure 10. *Test 2.*

To correct the failure from test 2, the Teflon gaskets were changed to silicon carbide to withstand the high heat. When running the third test there were warnings due to a boundary condition, it was determined that the issue was a buildup of pressure with the solution being to install a bypass valve. The results of the test can be seen in Figure 11 which additionally shows a graph that contains the temperature of the hot inlet water (shown in Green) and the cold inlet water (shown in Red). The graph shows how separated the different temperatures start and with the fluids flowing through the heat exchanger they begin to stabilize in temperature which lowers the hot inlet temperature from 323 C to an average of 249 C and the cold inlet temperature raises from 200 C to 254 C. The y-axis of the graph shows the temperature ranges, and the x-axis is the number of cycles that it produces of simulations.

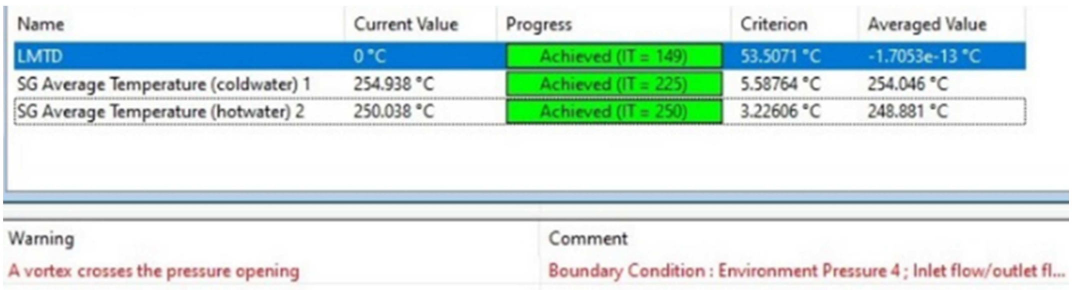


Goal plot 1

Name	Current Value	Progress	Criterion	Averaged Value
LMTD	0 °C	Achieved (IT = 150)	53.4973 °C	-1.7053e-13 °C
SG Average Temperature (coldwater) 1	254.745 °C	Achieved (IT = 225)	5.5928 °C	253.984 °C
SG Average Temperature (hotwater) 2	250.211 °C	Achieved (IT = 250)	3.32875 °C	249.004 °C

Figure 11. *Test 3.*

For test 4 in Figure 12, every variable stayed the same, with the plate changing from aluminum to copper. The heat transfer was slightly better, the cold water absorbed 0.062 C more than aluminum while the hot water cooled down by.123 C compared to aluminum.

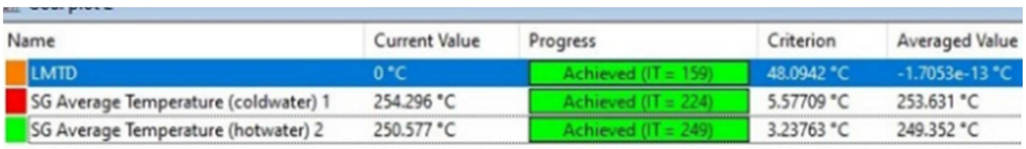


Name	Current Value	Progress	Criterion	Averaged Value
LMTD	0 °C	Achieved (IT = 149)	53.5071 °C	-1.7053e-13 °C
SG Average Temperature (coldwater) 1	254.938 °C	Achieved (IT = 225)	5.58764 °C	254.046 °C
SG Average Temperature (hotwater) 2	250.038 °C	Achieved (IT = 250)	3.22606 °C	248.881 °C

Warning	Comment
A vortex crosses the pressure opening	Boundary Condition : Environment Pressure 4 ; Inlet flow/outlet fl...

Figure 12. *Test 4.*

Test 5, as shown in Figure 13 the aluminum plates were changed to titanium to see if there would be any further improvements compared to copper which led to no sufficient findings of improvement.



Name	Current Value	Progress	Criterion	Averaged Value
LMTD	0 °C	Achieved (IT = 159)	48.0942 °C	-1.7053e-13 °C
SG Average Temperature (coldwater) 1	254.296 °C	Achieved (IT = 224)	5.57709 °C	253.631 °C
SG Average Temperature (hotwater) 2	250.577 °C	Achieved (IT = 249)	3.23763 °C	249.352 °C

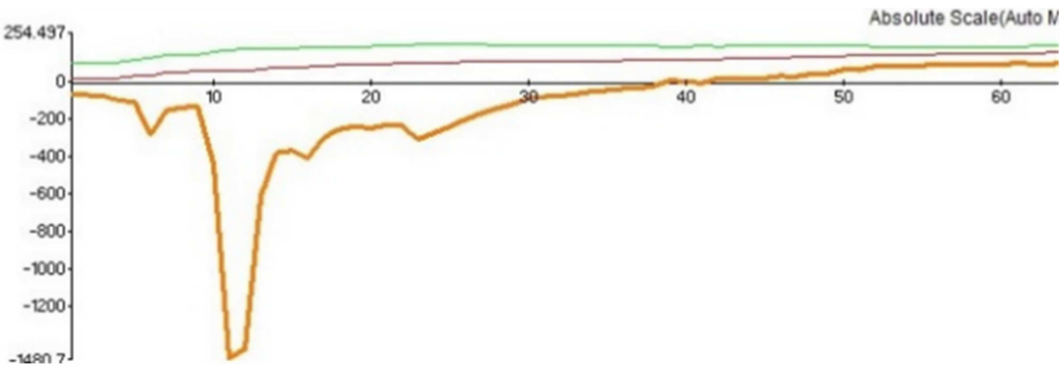


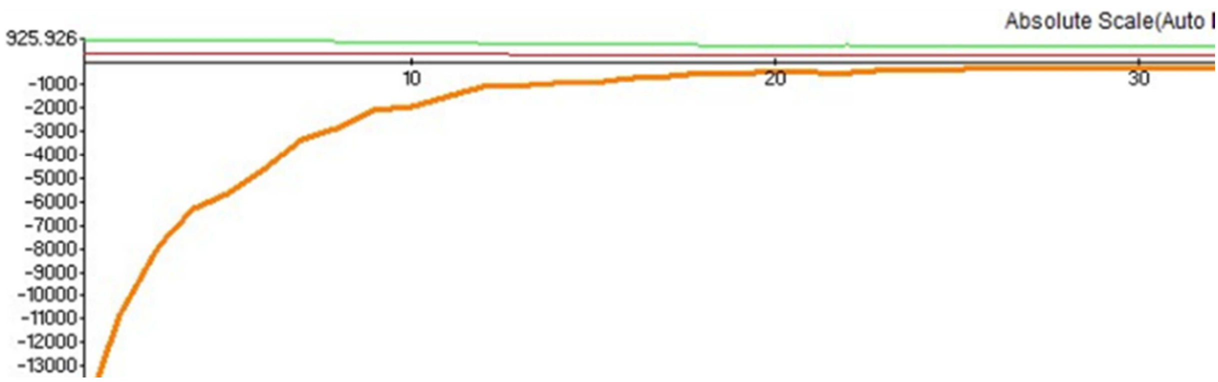
Figure 13. *Test 5.*

3.2. Results When Helium Is the Coolant

There are reactors and articles that are experimenting with Helium because of its usability in substantially higher degrees with temperatures being up to 1000 C. Helium is a comparable fluid for water as a coolant because of its low boiling point and the ability to rapidly cool any substance submerged in it. All the temperatures chosen for testing in the following experiments were chosen from a previous article [7].

In Test 6, it was to see how helium would perform because of its low boiling point compared to water, and with that change came different temperatures for the hot inlet changing to 950 C and the cold inlet being 350 C, the pressure was recommended to be at 7 MPa and velocity is set at 0.1 m/s. The results of increasing the temperature and pressure as shown in Figure 14 that aluminum could not withstand the test and melted.

Name	Current Value	Progress	Criterion	Averaged Value
LMTD	201.225 °C	Achieved (IT = 112)	243.414 °C	206.257 °C
SG Average Temperature (coldwater) 1	481.931 °C	Achieved (IT = 239)	4.66146 °C	480.317 °C
SG Average Temperature (hotwater) 2	771.315 °C	Achieved (IT = 182)	7.15524 °C	768.131 °C



Warning	Comment
A vortex crosses the pressure opening	Boundary Condition : Environment Pressure 2 ; Inlet flow/outlet fl...
	Boundary Condition : Environment Pressure 4 ; Inlet flow/outlet fl...
Solid is melting	Material: Aluminum ; Max temperature=660.934 °C; Melting temp...

Figure 14. *Test 6.*

By changing the plating material from aluminum to copper Test 7, Figure 15, showed that there was no melting warning as the previous test. The cold inlet did not absorb the same amount of heat from the hot helium outlet as aluminum did in the previous test, the cold outlet absorbed less than the aluminum by 6.711 C.

Name	Current Value	Progress	Criterion	Averaged Value
LMTD	170.41 °C	Achieved (IT = 114)	240.107 °C	163.203 °C
SG Average Temperature (coldwater) 1	475.684 °C	Achieved (IT = 234)	4.51444 °C	473.546 °C
SG Average Temperature (hotwater) 2	774.188 °C	Achieved (IT = 231)	7.24973 °C	774.078 °C

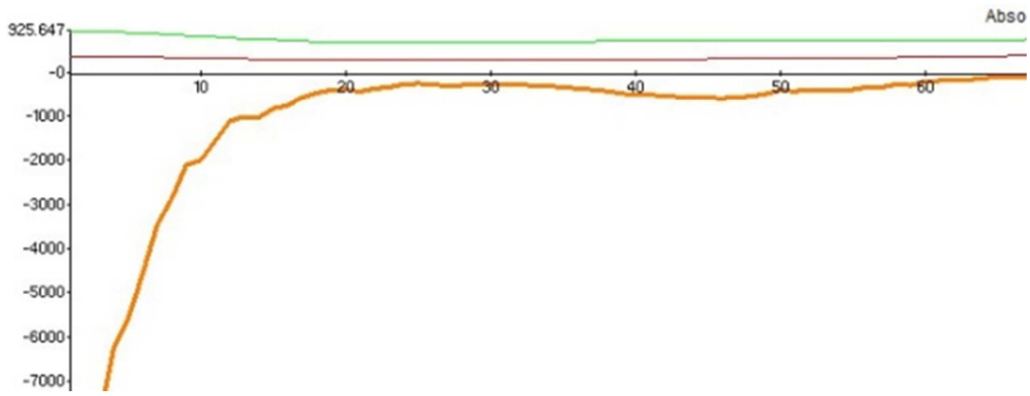


Figure 15. *Test 7.*

Test 8, as seen in test 4, can be determined that titanium is a recommendable material for high temperatures. In this test titanium outperformed copper substantially. The cold inlet absorbs more than 37.507 C and the hot outlet cooled down to 15.258 C, with all the heat transfer improvements titanium is still more expensive compared to copper.

Name	Current Value	Progress	Criterion	Averaged Val...
LMTD	317.301 °C	Achieved (IT = 97)	250.209 °C	318.256 °C
SG Average Temperature (coldwa	513.388 °C	Achieved (IT = 256)	5.17677 °C	511.053 °C
SG Average Temperature (hotwat	761.58 °C	Achieved (IT = 199)	6.45861 °C	758.82 °C

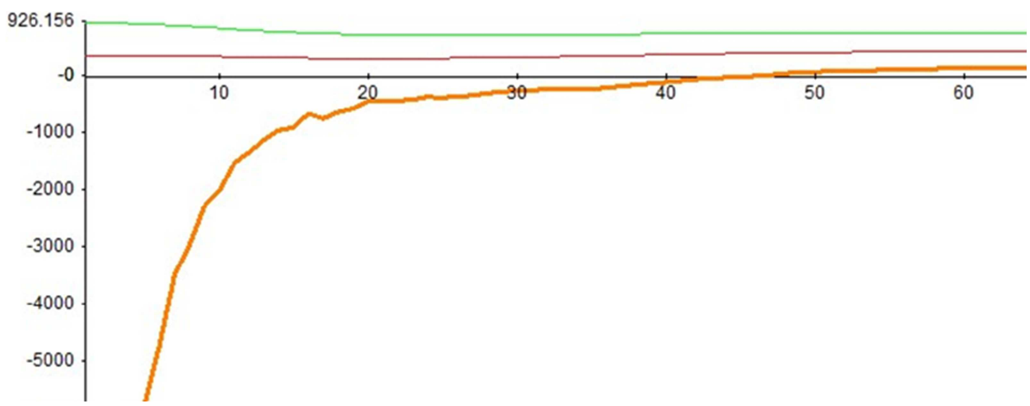


Figure 16. *Test 8.*

The final test test 9 Figure 17, was more experimental by changing the plate material to alloy 617, it did slightly better compared to titanium although the difference is not justifiable to the price difference.

Name	Current Value	Progress	Criterion	Averaged Val...
LMTD	319.43 °C	Achieved (IT = 97)	252.836 °C	312.09 °C
SG Average Temperature (coldwa	511.455 °C	Achieved (IT = 247)	5.19132 °C	509.162 °C
SG Average Temperature (hotwat	758.766 °C	Achieved (IT = 200)	6.48754 °C	759.455 °C

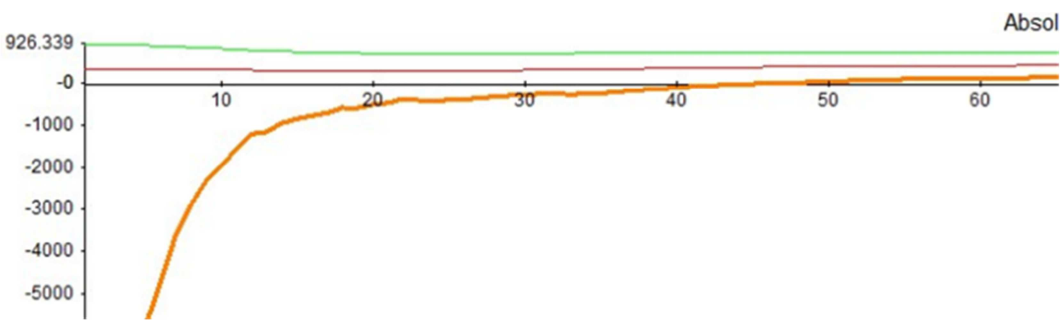


Figure 17. *Test 9.*

3.3. Discussion Regarding Results

In water, aluminum (Test 1 & 3), copper (Test 4), and titanium (Test 5) behaved differently. Copper had better heat absorption than titanium and aluminum by reducing the inlet water temperature to an average of 248 C from 323 C compared to reducing it to 249 C which was done by titanium and aluminum as shown in Figure 18, which shows the tests done by using water as the coolant. The best material for the plate for heat transfer in water was copper as it outperformed the other two materials because of its heat-exchanging capabilities at the desired temperature. Although, the difference in the outlet temperature in copper has a difference of 1 C compared to the other materials, which shows that the other materials are still suitable for future heat exchange tests.

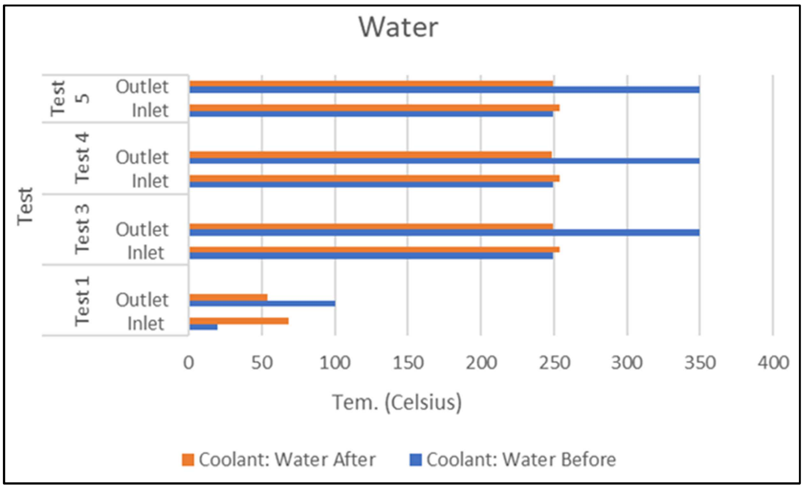


Figure 18. *Overall water results.*

On the other hand, with helium as a coolant, aluminum (Test 6), copper (Test 7), titanium (Test 8), and Alloy 617 (Test 9) showed differing results. As shown in Figure 19, Titanium outperformed the other two materials by lowering the hot outlet temperature to an average of 758 C from 950 C, compared to 768 C from Aluminum, 774 C from Copper, and 759 C from Alloy 617. The transferability of heat that can be done with Titanium in higher degrees of temperature can be seen since it can lower 192 C from the starting point while sustaining the pressure and temperature of helium. Alloy 617, being a combination of nickel, chromium, cobalt, and molybdenum alloy, was the most comparable to Titanium being only 1 C above however comparing the prices of both materials, Titanium is more economical.

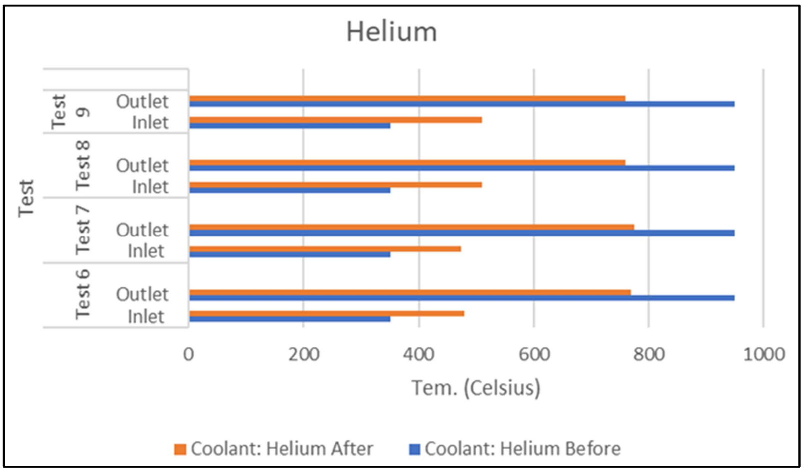


Figure 19. *Overall helium results.*

Throughout all the tests that were performed many different applications can be found about the heat retention and heat expulsion that occurs during them. The most notable findings from the tests performed are that the water and helium tests gave different results as to which material worked best in that environment, it is important to note that the temperature that was being used for the inlet and outlet temperature for the fluids were different since helium thrives in higher temperatures compared to water. Copper performed the best in water simulation tests by its optimal heat absorption and in helium simulation tests titanium performed the best in heat absorption, it is wise to note that this research does not only focus on the heat absorption of materials since the purpose is to find information that may better the future of small modular reactors.

One year from this point in time this research could be implemented into physical testing while at the same time building the theoretical model and being able to test all the different simulations that were performed through SolidWorks. Up to this point, everything was performed in a computer environment that can only show the results to a certain extent, all the tests performed were run through simulation and given to the researchers as graphs and text that were shown in the results section. Furthermore, the accuracy of Solidworks is less compared to more expensive and less accessible programs that could give results with more accuracy.

4. Conclusion

The purpose of various tests with multiple plates, gaskets, and fluids is to find the most effective version of the plate heat exchanger. Other tests are still presented with the fact that they might be useful to a consumer that would not be interested in or need the best version of a heat exchanger. Running tests regardless of failure or success can help further investigate thermal properties to optimize efficiency. This research may serve as a starting point for future research so as to not have to recreate tests that were proven to not be needed or successful. Overall, the heat exchanger tests that were completed are targeted to the needs of consumers and these findings have better prospects for future research.

Acknowledgements

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