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APPLIED NUMERICAL ANALYSIS ON THE DEVELOPMENT AND OPTIMIZATION OF AN AIR CODITIONIING DEVICE

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Abstract. *In this work an air conditioning device was built with easy to find materials, and variables such as the velocity and temperature of the out coming air were measured. After that, the model was tested using the Ansys' software with the purpose of visualizing the efficiency of the device as well as to implement some optimization in order to increase the quality of a possible selling product. The model was drawn using ANSYS DesignModeler and then the mesh corresponding was constructed with ANSYS Mesh, in order to input the data into the ANSYS Fluent software. Inside fluent both the boundary conditions and the materials used were specified and the simulation was initialized. After the result processing it was possible to compare the simulation and the measured experimental data and calculate the percentage relative errors as well as to implement some optimization such as an increase on the number of pipes inside the device and the exchange of its material. The analysis described above was able to prove the reliability of the method used, whereas the results obtained with the software were approximately the same as the experimental ones. The optimization implemented also demonstrated an increase on the quality of the out coming parameters.*

Keywords: *Fluid Mechanics, Air Conditioning, Numerical Simulation, Optimization*

1. INTRODUCTION

Heat exchange is been a matter for men for many decades as the effects of warmth disturbs human comfort and can cause damage on any moving machinery. With this in mind, Willis Haviland Carrier developed the first air treatment device in 1902 (Carrier, 2013). According to (Neves, 2018), the application of Carrier's invention was industrial at first, with a device that would condition the environment of a textile power plant by the reduction of the air temperature through artificially cooled pipes.

The first air conditioning devices utilized toxic and inflammable gases such as ammonia and propane as stated on (Neves, 2018). An occasional leak of these products could not just endanger the near population, but would also contribute to the destruction of the environment as CFC gases cause the destruction of ozone. Due to this fact, in 1987, the Montreal Protocol was signed as an international agreement to reducing the presence of CFCs on cooling devices as found on (Condicionado, 2013).

According to climatologists from (Baraniuk, 2018), 16 of the 17 warmest years registered occurred since 2001, which means that the world is in fact becoming hotter. This increase in temperature results in more air conditioning devices being commercialized and consequently the energy consumed by these should triplicate by 2050 according to the International Energy Agency. This increase on the demand for electric energy in additional to the environmental causes, put forward researches for devices that would consume less electric energy and cause the least damage to the environment (Alves, 2014).

Computational fluid dynamics 'CFD' is a tool that offer quantity previsions about fluid flow occurring under defined conditions. Since Kopal's work (Anderson, 2008), in 1947, this simulation method is going through a massive expansion as newer software are being released and free online training is present all over the internet as stated on (Ferziger and Peric, 2001). It is notable that, among other causes, this increase in popularity is due to the method's reliability of simulating complex real scaled models under an infinity of turbulence regimes and very detailed boundary conditions. People all around the world can model and test about any type of problem without constructing a physical model which is often very expensive and time consuming. The information found on the software can also be shared as wanted with almost no effort.

The concept of optimization defined by (Wang, 2018) as quantitative and systematic methodologies to improve products and processes efficiency is often utilized on 'CFD' numerical simulation. Optimization based 'CFD' simulations are crucial to research and product development due to the current need of decreasing the waste of resources.

In order to both develop an air conditioning device that would comply with the current environmental causes and prove

that the computational fluid dynamics simulations are effective on analysing fluid flow problems, a model was built and numerically simulated. The information taken from the measurements performed on the actual model were confronted to the simulated results and subsequently a series of optimizations were implemented to the computational model in order to both prove the software’s capacity and to increase the efficiency of the product developed.

The device’s system of operation consisted of the open cycle exposed on Fig. 1. First, water and ice were mixed into the bottom plastic bin so that when the water pump started the water would be transported to the top bin and by gravity would fall through the pipes located inside the assembled box. At the same time the fan would force air into the entrance and consequently it would flow between the pipes being released on the other side of the box with a lower temperature.

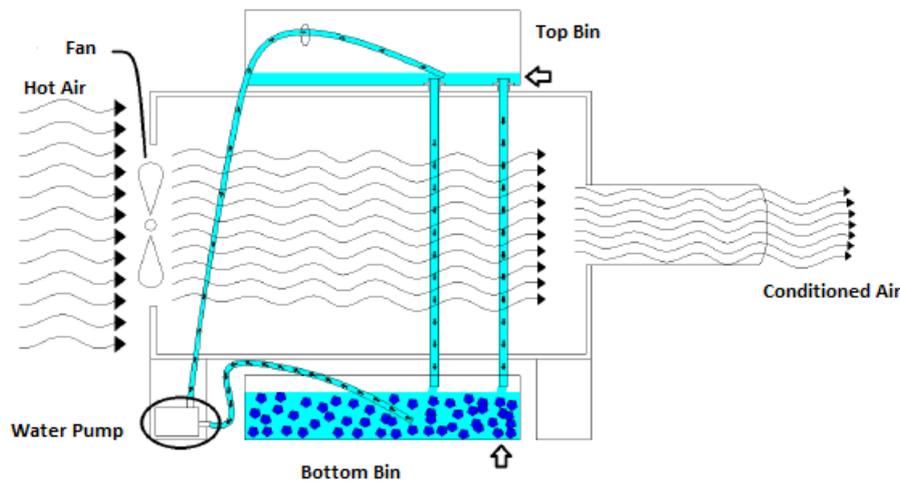


Figure 1. Function Diagram of the built model.
 Source: Author’s Record.

2. PROCEDURES

2.1 Model Assembly

For the construction of the experimental model the materials listed on Tab. 1 were utilized. The choice of materials focused on reducing cost at most and also on preventing environmental damage as can be seen on Fig. 2.

Table 1. List of materials.

Item	Quantity	Unit	Materials
1	1	un.	MDF Plate 2750 mm x 1803 mm x 10 mm
2	5	un.	Styrofoam Plate 1000 mm x 500 mm x 15 mm
3	3600	mm	25 mm Weldable PVC Pipe
4	300	mm	150 mm PVC Pipe
5	2	un.	28 L Plastic Bin
6	1	un.	Silicon Sticker
7	2000	mm	Garden Hose
8	44	un.	Wood Screw
9	1	un.	127 V Water Pump
10	1	un.	White Glue
11	1	un.	127 V Fan
12	2	un.	Metal clamp
13	200	mm	Cotton String

The air conditioning device was built in accordance to the following steps:

Step 1: The MDF and Styrofoam plates were sectioned so that two pieces of each material would have 800 mm x 250 mm ,800 mm x 520 mm and 500 mm x 500 mm. These measures correspond respectively to the right side, left side, top, bottom, rear and front side of the device.

Step 2: The Styrofoam plates were glued to the MDF plates of same dimensions with simple white glue.

Step 3: The plates formed a box of 500 mm x 520 mm x 800 mm which had its edges united by screws.

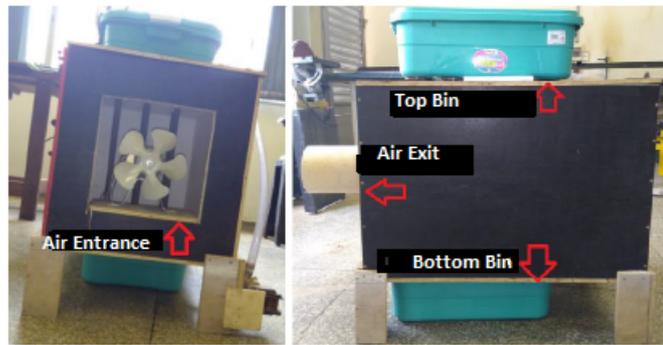


Figure 2. Model Built.
Source: Author's Record.

Step 4: The front side of the box was punctured in a way that a 150 mm PVC pipe would be fixed on it. This pipe represents the air exit and has the aim of avoiding the interference of surrounding air on the measurements.

Step 5: The 25 mm weldable PVC pipe was sectioned into six 600 mm parts and put through the assembled box with a gap of 50 mm on the top and bottom halves. The fixation was done with silicon stickers.

Step 6: On the rear side of the box a 300 mm x 300 mm square was cut through representing the air entrance. A fan and its holder were fixed.

Step 7: Two plastic bins were fixed respectively on the top and bottom pipes that remained out of the box so they could store the water used in the system.

Step 8: The garden hoses were fixed with metal clamps on the income and outcome pipes of the water pump.

Step 9: In order to make the measurements more precise a cotton string was attached to the 150 mm. The string was marked with 14 dots with intervals of 10 mm between each as exposed on Fig. 3.

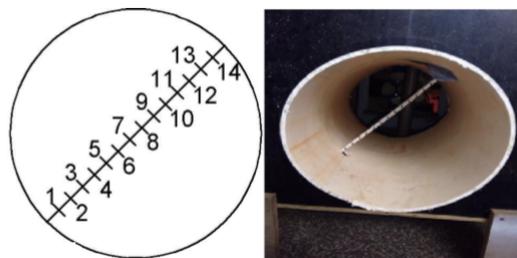


Figure 3. Auxiliary pipe described on step 9.
Source: Author's Record.

2.2 Experimental Analysis

The analysis were performed at the Engineering Laboratory of the Federal University of Grande Dourados where the device studied was fired and measurements of velocity and temperature were taken for the out coming air. The outside temperature of the PVC pipes were also measured.

The data was obtained with an anemometer from Instrutherm, the device used was a TAFR-180, insofar the temperature was measured with an infra-red thermometer from Icel named TD-965.

The anemometer's sensor was introduced into the out coming fixed pipe where values of temperature and velocity were taken for each of the 14 marks on the cotton string. The inside pipes' temperatures were taken by pointing the indicative laser to its direction.

The procedures described were considered because of its high precision and low cost.

2.3 Numerical Analysis

For the numerical analysis *Ansys 19 R1 Student Version* was utilized. Figure. 4 indicates a series of steps that were performed inside the software so that the calculations could be concluded. The choice of this software was based on how respected it is on the industry and academic community as well as on its robustness. The student version was picked because it is an open source platform.

The already described device was drawn into the *Design Modeler* feature. In order to decrease the number of elements

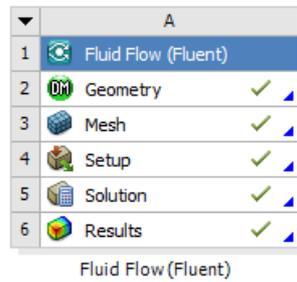


Figure 4. Steps of Numerical Analysis.
 Source: Author’s Record.

in the simulation and respect the constrains of the chosen software, a circle was drawn around the pipes as shown on Fig. 5, so the boundary layer would be present when the mesh is composed. The geometry could have also been imported from non-ansys software.

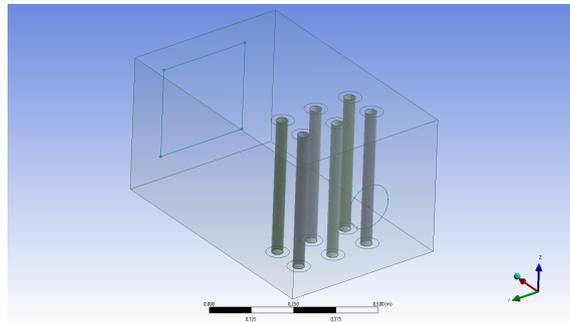


Figure 5. Designed Device with highlighted boundary layers .
 Source: Author’s Record.

The mesh was generated on *Mesh*, where a series of parameters were monitored in order to control the effects of the mesh on the final results. The final mesh design utilized had an average aspect ratio of 1,86 and an average element quality rate of 0,83. The described mesh contained 508,937 hex-structured elements and 148,872 nodes.

The next composing step was inserting the pertinent boundary conditions to the model. The experimental data acquired for the out coming velocity of air in addition to a brief calculation based on the continuity equation as shown on Eq. (1) were utilized in order to determine the out coming air velocity.

$$V_{in} = \frac{V_{out} * A_{out}}{A_{in}} \tag{1}$$

$$V_{in} = \frac{3.75 * (\pi * 0.0715^2)}{0.3 * 0.3} \tag{2}$$

Where:

- V_{in} = Incoming air velocity.
- V_{out} = Out coming air velocity.
- A_{in} = Air entrance area
- A_{out} = Air exit area.

As a result, the calculated incoming air velocity was $V_{in} = 0.694$ m/s, the incoming air temperature was setted as room temperature which was 294.1 K on the day that it was measured and the incoming water temperature was setted as 273 K as it was represented by an ice-water mixture.

The velocity of the cold water was determined by a simple procedure where the actual model’s hose was linked to an alternative bowl and the time that it took to fill it up was measured. With the defined area of the bowl it was possible to calculate de velocity of the water which was 0.2 m/s.

As the problem involves forced convection, the radiation effects were despised. The simulation performed 60 iterations and the convergence criteria used can be observed on Tab. 2.

After the determination of the described criteria, the calculations were performed on *Fluent*. The solution method used by ANSYS Fluent was Finite Volume and the considered turbulence model was the realisable k-Épsilon because this is

Table 2. Convergence Criteria.

Criteria	Residue R
Velocity	1.00E-03
Energy	1.00E-07
Turbulence Kinetic Energy (k)	1.00E-03
Turbulent Kinetic Energy Dissipation Rate	1.00E-03

the most common used regimen for turbulent flow conditions. The acquired data was then automatically sent to the 'CFD' post window where the final processing were executed.

Besides the out coming air temperature and velocity, the refrigeration capacity parameter is adequate on describing the efficiency of cooling devices. According to (Corrêa, 2010), the refrigeration capacity is defined by the heat transfer rate between the air and the refrigeration fluid and can me written as:

$$\dot{Q}_0 = \dot{m}_{ar}(h1 - h4) \quad (3)$$

Where:

\dot{Q}_0 = Refrigeration Capacity.

\dot{m}_{ar} = Mass Flow.

$h2$ = Exit Enthalpy.

$h1$ = Entrance Enthalpy.

In order to validate the accordance between the experimental and simulated data, the relative percentage error rate of the out coming air temperature was calculated. In consonance with (Canale, 2008), the error parameter can be calculated by:

$$Er = \left| \frac{xi - xv}{xi} \right| \cdot 100 \quad (4)$$

In which is read:

Er = Relative Percentage Error Rate.

xi = Real Value Acquired.

xv = Value Expected.

3. RESULTS AND DISCUSSION

3.1 Experimental Results

Firstly the room temperature (T_{amb}) was measured with the anemometer which delivered a value of $T_{amb} = 294.1$ K. In order to acquire the outside temperature of each pipe, the infra-red thermometer's laser was pointed at the top part and then at the bottom part of the six existing pipes, so the results obtained are the average values of these two measurements as shown on Tab. 3.

Table 3. Average Outside Temperature of PVC Pipes.

Pipe	Area	Measured Temperature (K)	Average (K)
1	Top	286.6	
1	Bottom	285.7	
2	Top	283.5	
2	Bottom	284.8	
3	Top	284.8	
3	Bottom	285.6	
4	Top	285.6	285.2
4	Bottom	286.1	
5	Top	284.1	
5	Bottom	285.3	
6	Top	284.7	
6	Bottom	286.1	

For the out coming velocity and temperature of the air the anemometer was used and values were obtained for the 14 markings on the already described string. The values of T_{out} and V_{out} attained were processed and the average calculated as can be seen on Tab. 4 and Tab. 5.

Table 4. Velocity of Out Coming Air.

Variable	Marking	Value (m/s)	Average (m/s)
V_{out}	1	3.1	3.75
	2	3.4	
	3	3.7	
	4	3.6	
	5	3.6	
	6	3.8	
	7	4.0	
	8	4.0	
	9	4.0	
	10	4.0	
	11	4.0	
	12	3.9	
	13	3.8	
	14	3.6	

Table 5. Temperature of Out Coming Air.

Variable	Marking	Value (K)	Average (K)
T_{out}	1	292.90	292.55
	2	292.90	
	3	292.70	
	4	292.70	
	5	292.50	
	6	292.50	
	7	292.10	
	8	292.10	
	9	292.10	
	10	292.30	
	11	292.50	
	12	292.60	
	13	292.90	
	14	292.90	

For the calculation of the experimental device's refrigeration capacity, the mass flow was calculated based on the velocity results and the area of the out coming port. The initial and final enthalpies were obtained from a consultation on (Shapiro, 2006). The parameters provided to Eq. 3 are listed on Tab. 6.

Table 6. Data for the refrigeration capacity calculation.

Parameter	Value	Unit
\dot{m}_{ar}	0.071	kg/s
h_1	294.26	kJ/kg
h_4	292.66	kJ/kg

The calculated refrigeration capacity calculated in accordance with Eq.(3) was $Q_0 = 110$ W. The low value can be explained by the purpose of the device design, which is to reduce the local air temperature with low cost and energy demand.

3.2 Numerical Results

In order to validate the chosen procedure the results obtained with the simulation were compared to the experimental values acquired. All the data presented on this section was taken from the CFD Post software.

The temperature field was obtained and the average temperature of each pipe was calculated as shown on Tab. 7.

Table 7. Average Outside Temperature of PVC Pipes.

Pipe	Measured Temperature (K)	Average (K)
1	275.47	
2	275.90	
3	275.64	
4	275.98	275.71
5	275.40	
6	275.88	

The average velocity and temperature of the out coming air are displayed on Fig.6 and Fig.7 respectively.

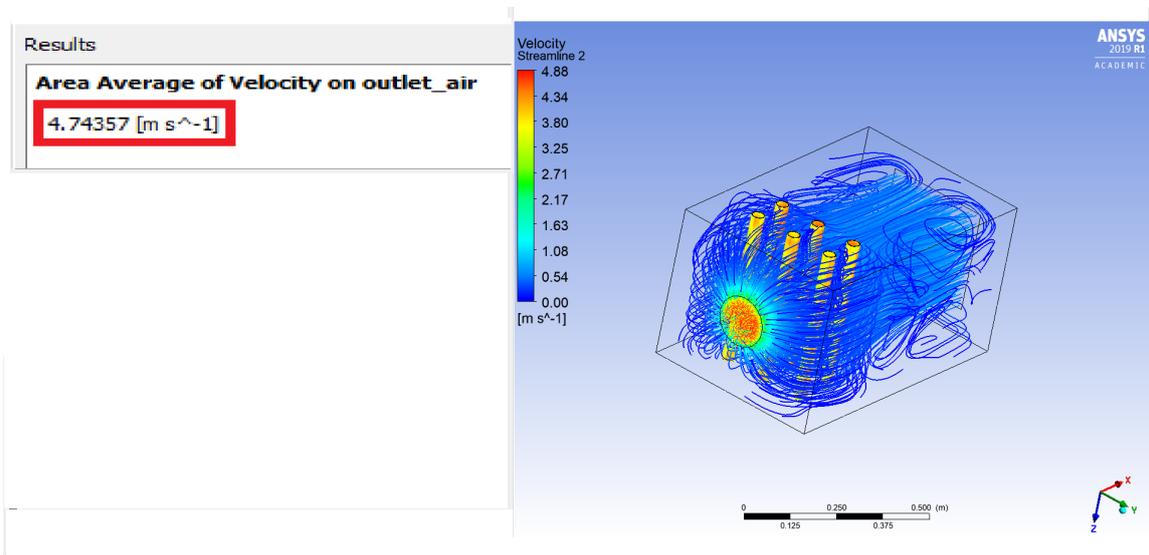


Figure 6. Average Out Coming Velocity of Air.
 Source: Author's Record.

The refrigeration capacity calculated for this analysis utilized the temperature and velocity data from Fig.6 and Fig.7. The value acquired was $Q_0 = 62.86$ W.

3.3 Discussion

The relative error percentage rate in relation to the the out coming air temperature was calculated according to Eq.(4) and the result showed an error percentage of 0.29 %. This value exposes a minor disparity between the results obtained with the experimental analysis and the simulation.

The minor discrepancies on the values obtained may be due to measurement errors present on the experimental analysis as well as to the limited number of elements used on the simulation because of the academic version's limit. Despite that, according to the results displayed, the simulation method used describes with a high level of reliability what occurs on the real life model.

4. OPTIMIZATION

4.1 Area Optimization

The numerical simulation performed yielded some visual problems on the project developed, which opened a gap to an area optimization. As shown on Fig.6, there are some recirculation areas on the inside of the box, this phenomenon causes an energy waste that can be converted to performance if eliminated.

With that in mind, the device was redesigned and the out coming temperature was acquired as shown on Fig.8.

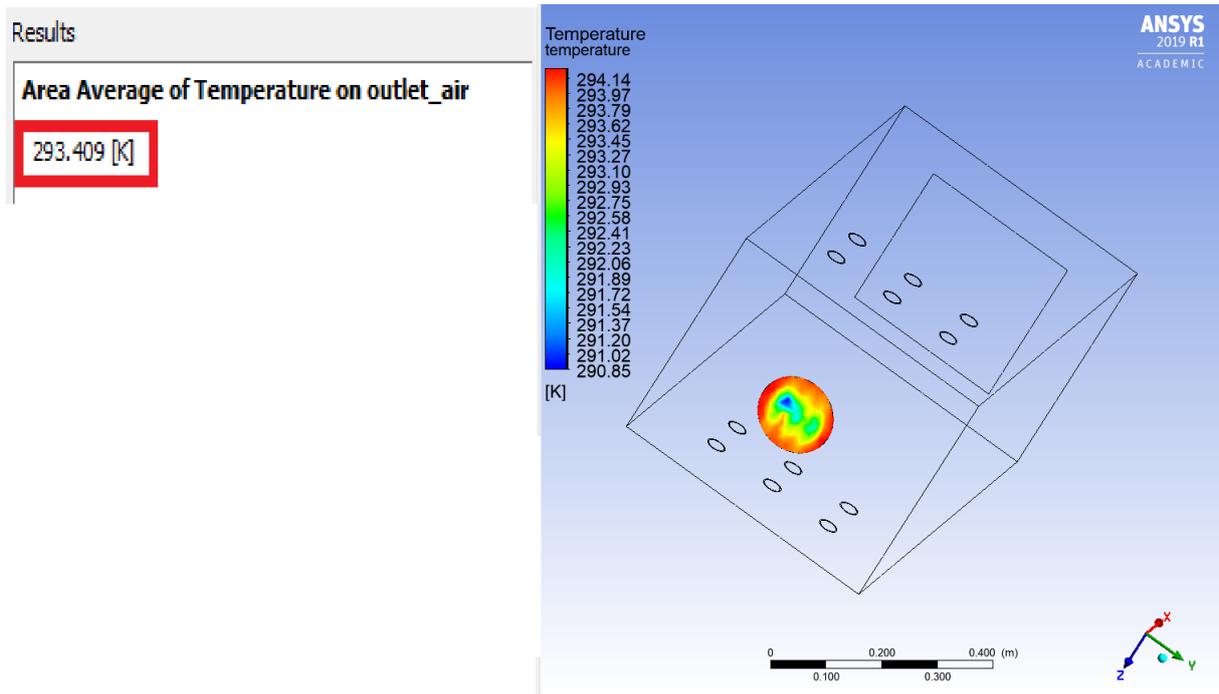


Figure 7. Average Out Coming Temperature of Air.
Source: Author's Record.

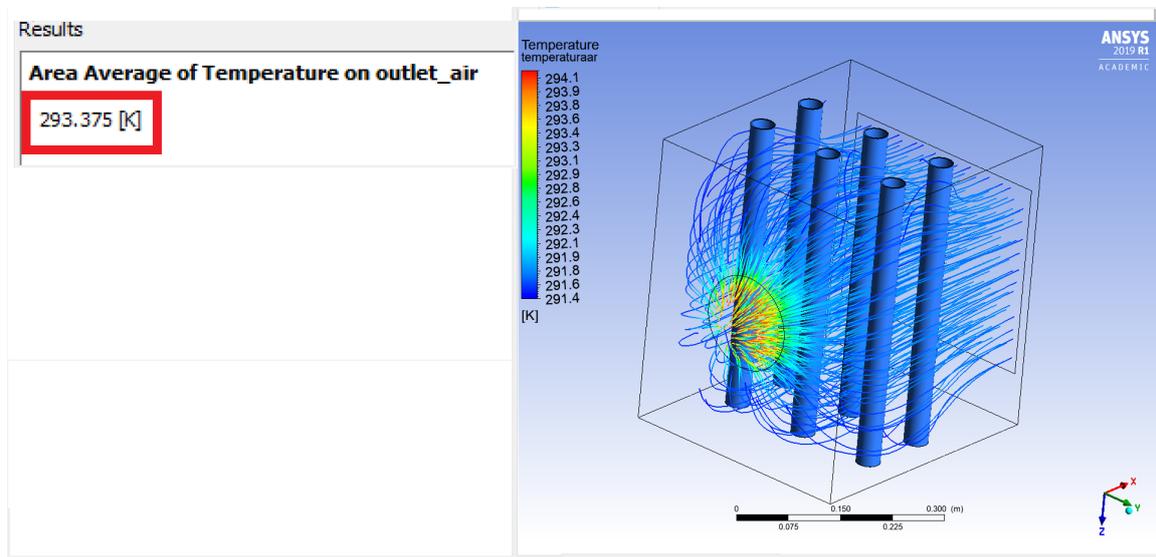


Figure 8. Out Coming Air Temperature for Optimized Model (Area).
Source: Author's Record.

The image above shows the absence of recirculation areas and the calculated temperature value obtained decreased in comparison to the previous simulation which validates the procedure performed. In addition to the device's efficiency, this area optimization reduces the amount of material needed for its construction which is both environmental and costly effective.

4.2 Material Optimization

In order to further the studies on the device's efficiency, the previous optimization was kept and the material of the pipes was modified. Instead of PVC, copper pipes were introduced and the proper simulations were performed. The copper pipe was chosen based on its conductive coefficient, which is significantly larger than the PVC's. This modification would bring the model to be more expensive, but the increase in efficiency was expected to overcome by far this downside.

The results obtained for this case are shown on Fig. 9.

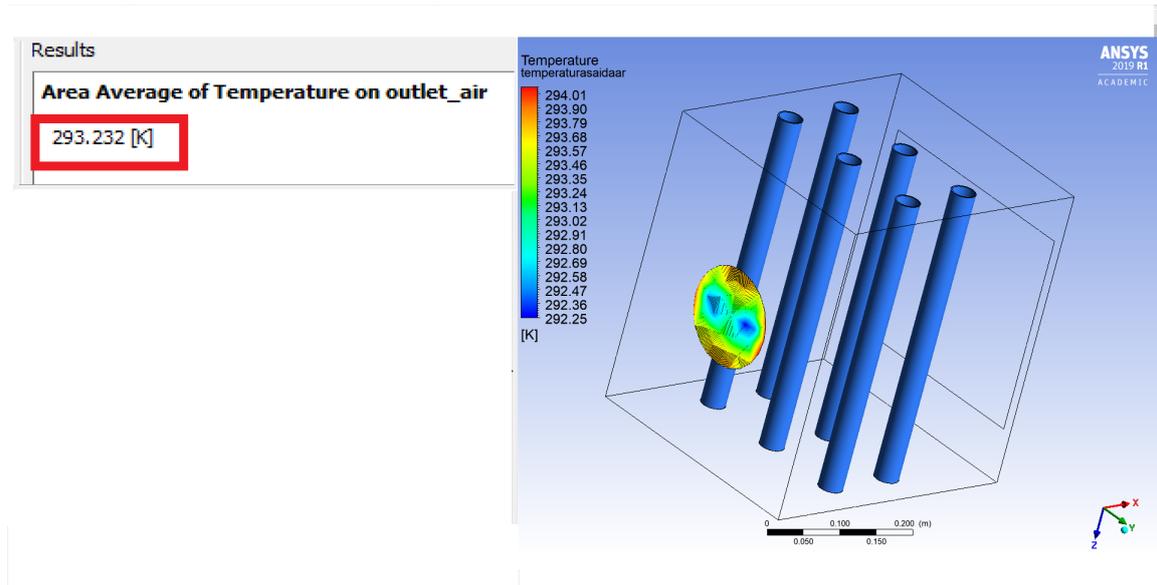


Figure 9. Out Coming Air Temperature for Optimized Model(Area + Material).

Source: Author's Record.

According to the image above, the decrease on the out coming air temperature had roughly 0.1 K on magnitude which is not sufficient to cover the increase in cost of the project. This phenomenon was not expected due to the great discrepancy between the conductivity coefficients of the materials used, however it can be justified by the thickness of the pipes' walls.

5. CONCLUSION

The analysis performed testified the success of the method used such that both the experimental and the numerical analysis delivered equivalent reasonable results. The numerical analysis was satisfactory proving that the student version of *Ansys* is effective on performing a variety of simulations.

For future works it is intended to develop and justify a set of additional optimizations to the original model so that the efficiency of the product is improved and its cost decreased. The number of tubes and their orientation can be modified as well as other features of the design can be optimized. The challenge is to adequate these modifications and the reliability of the results with the reduced number of elements delivered by the version of the software used.

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7. RESPONSIBILITY NOTICE

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