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ENHANCEMENT OF PULLEY AND BELT MECHANISM USING FINITE ELEMENT ANALYSIS

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Abstract— The pulley and belt mechanism has been developed to supply the needs of power transmission. This mechanism and especially the V-belt drive mechanism is widely used in the agricultural industry, however, it is facing numerous challenges due to the heat generated in the belt during its operation. The rate of hysteresis loss induced by the frequent use of the belt is important which made it a major concern for engineers. The heat produced on the contact surface during the process under the effect of friction is transformed into heat, which leads to the degradation of the microscopic polymer molecular chains and the fast aging of the rubber part, therefore it adversely impacts the durability of the V-belt. To tackle this encountering problem, we have conducted a thermal study using finite element simulations on a pulley and belt mechanism. We sight to improve the design by adding the so-called cooling fins to the pulley, mainly to increase the heat transfer area and reduce the temperature of the pulley, hence improve its efficiency along the service life. And by examining these new models using finite element methods (FEM), the results show a decreasing in the temperature, therefore increasing in the lifetime of the belt is expected and reduce the problems which occur in high temperature.

I. Introduction

The heat generated from a belt drive system is highly related to the power loss during its operation because the last is converted into heat, then dissipated to the environment through the surfaces of the different parts of the system. Many developed theories and experimental studies were conducted to enhance the belt drive system efficiency, The most prevalent theory for both flat and V-belt drive systems elucidate the delivery power loss in the pulley belt mechanism by the following five contributions: the belt bending, belt radial compression, belt tension, belt shear, and belt–pulley slip [1]. The first four types of power loss occur because of the belt hysteresis, whereas the last type of power loss could be attributed to the slipping of the belt against the pulley's outer surface. [2] expanded this theory to a poly-v-belt transmission, which involves the combination of flat and V-belts. [3][4] focused on the power losses owing to the belt hysteresis caused by the dynamic bending, stretching, shear, flank, and radial compression of the belt rubber, and they further considered other losses such as the bearing loss in the belt transmission. Another theory classified the power losses into three types: frictional sliding, belt longitudinal, and lateral material hysteresis, and frictional losses owing to the engagement/disengagement of the belt at the entrance and exit from the pulleys [5]. However, another existing study indicated that the slip loss between the belt and pulley is the main cause of power loss in belt drive transmissions [6].

V-belt drives are commonly used for power transmission in various industrial and agricultural Machinery. The transfer of power is mainly dependent on friction which has both advantages and disadvantages. As an advantage, the drive part is made of an elastic material which protects it from the effect of overloading. Moreover, [7] showed that the variation of the loading amount impacts the friction also ensures that the transmission (i.e., the motion of the operated equipment) can differ between certain limits due to the slip and can therefore only be used in certain places where this is not an inconvenience.

One of the major factors impacting the V-belt lifetime is the temperature generated within the belt, which is determined by the operating environment temperature and the drive's operating characteristics (i.e., drive speed, load, drives dimensions, etc.). The efficiency of the belt drive could be evaluated from the steady temperature of the operating V-belt if it is tested as loss intensity [2]. Pulleys are used in high torque/speed power transmission systems, and they are manufactured using fiber-reinforced polymers (FRPs) which put it at a higher risk of thermal deterioration [1]. The heat generated from the torque/speed loss accumulates inside the belt material due to the low thermal conductivity of the FRPs which may damage the belt material itself, hence reduce its lifetime [2]. The high temperature generated with the belt results in the breakdown of polymer molecular chains which in turns causes ageing of the rubber material and significantly affects the lifetime of the V-belt. According to the study conducted by [8] when the V-belt temperature exceeds 70°C, it results in a significant drop of its lifetime.

The power loss from the V-belt drive can be categorized into two classes, one is the loss caused by external friction (slip between the belt and the pulley), and the second is the loss caused by internal friction (slip between the molecules of the belt material so-called hysteresis). According to [3], the above losses could be more classified as per the belt and pulley parameters, for instance. The gradual slip effect that occurs during the drive operation is also a reason of power loss, this is recognized as external friction resulting from the slip of the belt. The other type of loss that can be categorized as external friction is the slip between the belt and the surface of the pulley when the belt enters and leaves the pulley. [4-6][9][10].

Some researchers concentrate on researching slip caused by creeping in the belt. The belt's friction and elasticity along the wrap angle is a distinction that can be made between the adhesion and slippage angular domains. This relative shift takes place between the pulley and the belt, resulting in heat generation as well [3] [11-13]. In addition to driving parameters such as operating conditions, polluted environment, temperature, and relative humidity as well as drive alignment errors. Its effect the involvement of the V-belt and the pulley, causing the elemental slips (relative motions). These macroscopic slips cause wearing in the belt and friction-generated heat affects the continuous power transfer and efficiency. The friction has a major role [14].

According to [8], after their experiment in the laboratory for the no load and medium load operation condition is has been found that the belt temperature increases, and it’s expected to increase more and more in loading operation conditions, and because of the High belt temperature resulted in the breakdown of polymer molecular chains and ageing of rubber materials, this greatly affects the life of the V-belt. The temperature of the V-belt above

70°C means that the lifetime of the belt decreases dramatically. If the temperature of the belt increases by 10°C, the belt lifetime decreased by the half of the original value.

Therefore, the task is to make a numerical Modell for the pulley and belt mechanism at 70°C, which is the temperature where the lifetime of the belt decreases dramatically and study the temperature of the pulley belt mechanism and heat transfer between the pulleys and the surrounding environment temperature and try to decrease the temperature of the pulley to decrease the temperature of the belt. But according to [15], the reduction in the belt temperature is smaller than the reduction in the pulleys temperature by average of (4°C) even though the belt and the pulley are in direct connection, but the shape factor and the materials different and the rest of the other factors play a role in this temperature difference, but even in this temperature difference we are able to decrease the temperature of the belt additionally an increasing in the lifetime of the belt and working optimum environment is expected, therefore it has been made a (FEM) simulation model for this mechanism.

II. Methodology

The temperature of the V-belt is determined by the equilibrium of the generated heat and heat loss. This is affected by several factors, namely, air temperature, humidity, temperature, and the heat capacity generated between the different parts, etc. Researchers investigated the temperature variation of the V-belt mechanism by conducting real experiments where the aforementioned factors were considered constant, then measurements were taken. Results showed that the temperature increased by, which means the power loss between the two equilibria – between the steady state of the workshop temperature and operating temperature.

According to [8], after their experiment in the laboratory for the no load and medium load operation condition is has been found that the belt temperature increases, and it is expected to increase more and more in the high load operation conditions, and because of the High belt temperature resulted in the breakdown of polymer molecular chains and ageing of rubber materials. This greatly affects the life of the V-belt. The temperature of the V-belt above 70°C means that the lifetime of the belt decreases dramatically. If the temperature decreases by 10°C, the lifetime increases to double its original value.

Therefore, the task is to make a numerical Modell for the pulley and belt mechanism at 70°C which is the temperature where the lifetime of the belt decreases dramatically and study the temperature of belt and heat transfer between the pulleys and the surrounding environment temperature and try to decrease the temperature of the pulley to decrease the temperature of the belt in order to increase the life of the belt and to reach the optimum working environment for the belt, therefore it has been made a (FEM) simulation model for this mechanism.

In this work, we sight to increase the V-belt lifetime by a new design.

A. Governing Equations

This The Fluid flow is described using the governing equations, Navier-Stokes equations which describe how the velocity, pressure, temperature, and density of fluid flow are related. One can say that Navier-Stokes equations are Newton's second law of motion applied to fluids. The effect of viscosity which has not been regarded in the Euler equations is considered in the Navier-Stokes equations. They are based on three conservation laws: conservation of mass, conservation of momentum and conservation of energy. The equations are partial differential equations which do not have a defined analytical solution and are therefore solved numerically [16][17].

Conservation of mass states that the rate of change of mass in an arbitrary material volume is equal to the rate of mass production in that volume as shown in Equation (1):

$$\frac{d}{d_t}\int_{V(t)} \rho(x_1 t)\, dV = \int_{V(t)} \sigma(x,t)\, dV \tag{1}$$

where:
$\rho(x, t)$ = Density of a particle
$\sigma(x, t)$ = Rate of mass production per volume at time t and position x

$\sigma(x,t) \neq 0$ is true only for multiphase flows and therefore taking $\sigma(x,t) = 0$ in Equation (1), we obtain the continuity as in Equation (2):

$$\frac{\partial \rho}{\partial t} + \nabla \rho u = 0 \tag{2}$$

Conservation of momentum states that the rate of change of momentum of a material volume is equal to the total force on the volume. Two kinds of forces act on a volume: body forces F_i and surfaces forces R_i. The conservation of momentum law can be written in integral form and using Reynold's transport theorem as presented in Equation (3):

$$\int_{V(t)} \rho \frac{Du_i}{Dt} dV = \int_{V(t)} \rho_{F_i}\, dv + \int_{S(t)} R_i\, dS \tag{3}$$

Furthermore, the surface forces must be transformed into a volume integral which is achieved by defining the stress tensor, T_{ij} in Equation (4). The stress tensor consists of an isotropic part, hydrodynamic pressure p and a viscous stress tensor, τ_{ij} which depends on the fluid motion.

$$T_{ij} = -\rho\delta_{ij} + \tau_{ij} \tag{4}$$

The momentum Equation (5) is then equal to:

$$\rho \frac{Du_i}{Dt} = F_i + \frac{\delta T_{ij}}{\delta xi} \tag{5}$$

For a Newtonian fluid, the relationship between the viscous stress and the strain is given by Equation (6):

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_r}{\partial xv}\delta_{i_j}\right) \tag{6}$$

Using this, the final conservation of momentum law of the Navier-Stokes equations is obtained as in Equation (7):

$$\rho \frac{Du_i}{Dt} = -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_r}{\partial xv}\delta_{i_j}\right)\right] + \rho F_i \tag{7}$$

Conservation of energy states that the rate of change of energy in a material particle is equal to the amount of energy received by heat and work transferred by the particle. The first law of thermodynamics stated as in Equation (8):

$$\frac{d}{d_t}\int_{V_{(t)}} \rho E \, dV = W + Q \quad (8)$$

where:
E = Total of energy
W = Rate of work done by the surrounding on the fluid ate of mass production per volume at time t and position x
Q = Rate of heat addition

Once again, the work done is divided into body force and surface force and Q is obtained by assuming that heat is added to each particle at a rate q per unit of mass and that there exists a heat flux σ per unit area of the surface which is governed by Fourier's law. Solving using these laws for the first law of thermodynamics we achieve the law of energy conservation as in Equation (9):

$$P\frac{De}{Dt} = -\rho\frac{\partial u_i}{\partial xj} + \frac{\partial_{4i}}{\partial x_j}\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_r}{\partial xv}\delta_{i_j}\right) + \frac{\partial}{\partial x_i} + \left(k\frac{\partial T}{\partial x_i}\right) \quad (9)$$

where:
k = Thermal conductivity

Computational Fluid Dynamics focuses on solving these problems with the help of numerical analysis and approximating the solution to Navier-Stokes with methods such as finite difference, finite volume finite element and spectral methods [16][17].

B. Numerical Model

Software based on the finite element method (e.g., ANSYS®, LS-DYNA®, ABAQUS®) have brought light to tackle various engineering problems such as material strength, hardening, elasticity, temperature distribution, fluid flow, etc. With the emergence of this powerful numerical tool, the old expensive trial-and-error method is no more useful. Figure 1 shows the developed numerical model to imitate a real process. The simulation was conducted at a steady 70°C temperature of the whole system. The Modell is composed of two parts, a pulley, and a belt in direct contact.

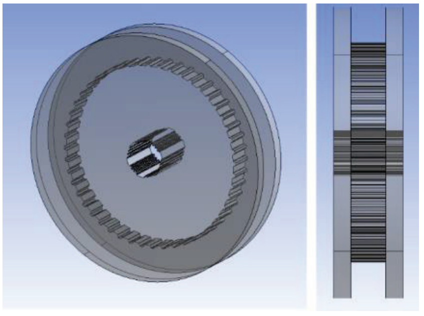


Figure 1: Original Model of the Pulley

The pulley has a diameter of 200 mm and a total thickness of 50 mm. In order to improve the model created above, we conceived a new design by adding fins along the pulley circumference as shown in Figure 2. The fins have both equal length and thickness of 20 mm and 1.5 mm, respectively. The role of the fins is to increase the heat transfer area between the V-belt system and the environment, in turns increase the speed of the air on the system surface, hence augment the convectional heat transfer coefficient.

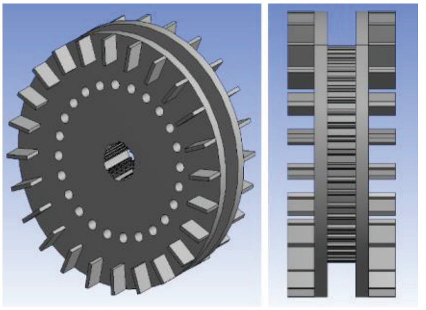
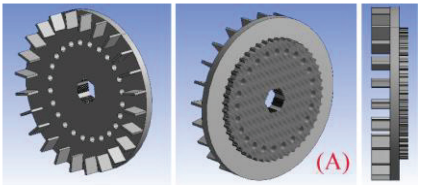


Figure 2: Modified Model of the Pulley

Finite element simulation could be time consuming if a large geometry having a big number of finite elements is used. With this numerical drawback in mind, we considered one half of the pulley in all the simulation as the system is asymmetric, furthermore, we removed the holes and teeth of the pulley's inner part since their impact on the airflow is trivial (Figure 3) and to reduce not only meshing errors but also meshing refinement.



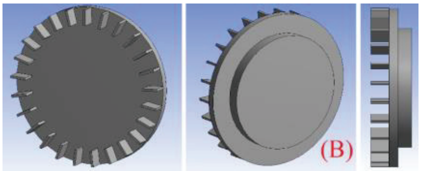


Figure 3: Half of the Model after Removing the Teeth and Holes

The model is now ready to be processed in the finite element methods program as shown in Figure 4. In Figure 5, the model has been drawn by adding the rotating zone and the open zone to simulate the environment operation conditions. The first model is the ordinary model without fins where the temperature at the highest point of the degradation in the rubber molecules (70°C) [7][8] the second model is the modified model where the new model is trying to eliminate the high temperature problem.

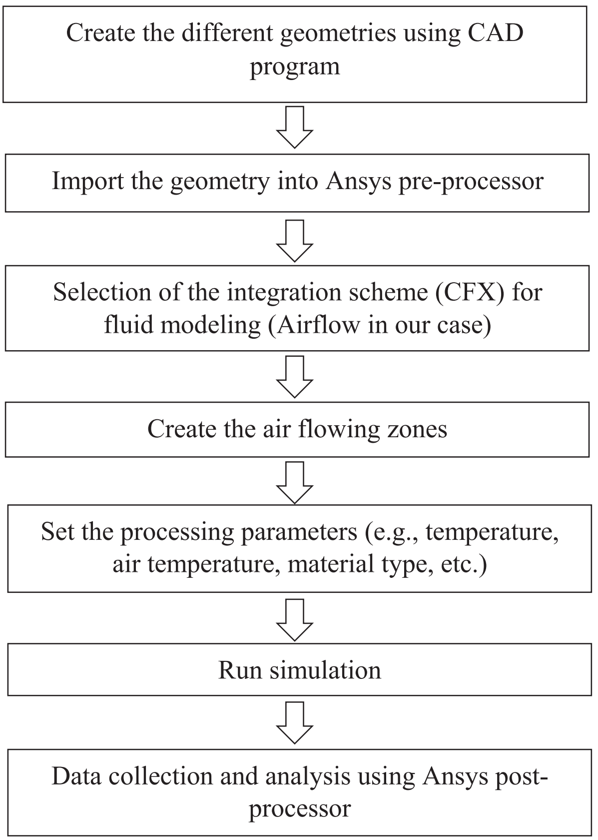


Figure 4: Schematic of the Finite Element Methodology

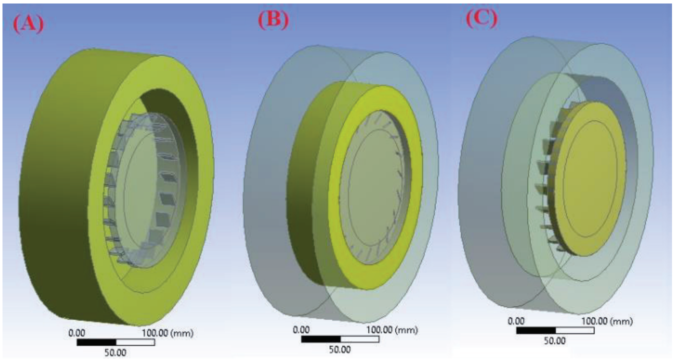


Figure 5: Different zones of the models (A) open air, (B) rotating air, (C) the pulley

C. Meshing Independence Study

As explained before, a CFX integration scheme has been utilized to investigate the efficiency of the different finite element models. A five different meshing size element were generated to solve the governing equations. The reason behind using different size element is to examine the mesh sensitivity regarding the model temperature and to obtain a high accurate result.

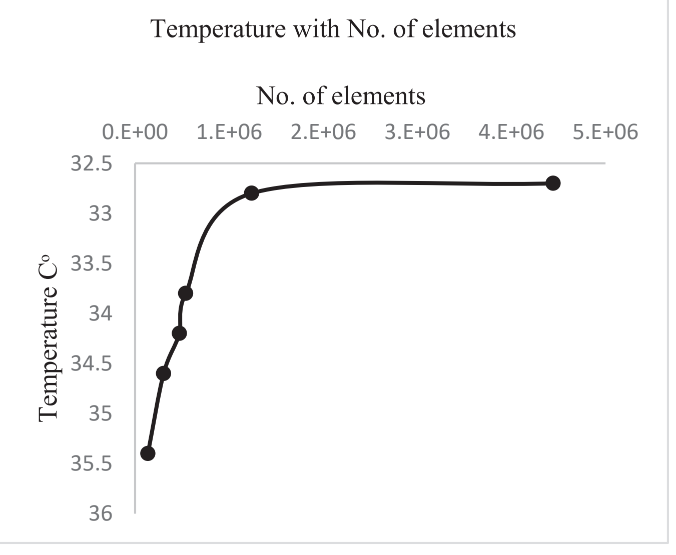


Figure 6: Temperature with number of elements

Figure 6 shows the impact of the number of elements on the accuracy of the result for one model 25 fins and 90 tilt angles, as shown when the number of elements exceeds one million element there will be no change on the accuracy of the temperature therefore, in all the upcoming results have been done on the number of elements of 1250000.

D. Boundary Condition

The pulley was rotating at 2000 rpm in all simulations, also the air temperature and pressure were kept constant at 25°C and 1bar, respectively.

Heat capacity generated from the pulley itself during the process was evaluated, for this reason we set the same value of heat flux for both models at 5075 w/m^2. We have chosen this value of heat flux by purpose because exceeding this given value, the belt temperature rises to 70°C and at this temperature magnitude the molecular chain of the belt material collapses. Therefore, we sight to improve this empirical model using “cooling fins” to reduce the temperature of the belt.

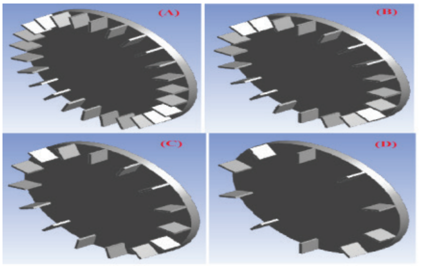


Figure 7: The modified models after adding the fins, Model (A) 25 fins, Model (B) 20 fins, Model (C) 15 fins, Model (D) 10 fins

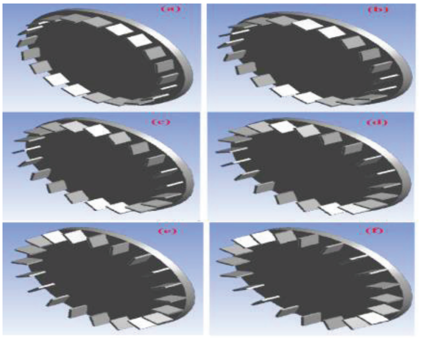


Figure 8: Model (A) 25 fins at different fins tilt angles, (a) 15°, (b) 30°, (c) 45°, (d) 60°, (e) 75°, (f) 90°)

Table 1: Design of Numerical Experiments

Runs	Number of fins	Fins tilt angle
1	No fins	--
2	25 model A	f 90

3	25 model A	e 75
4	25 model A	d 60
5	25 model A	c 45
6	25 model A	b 30
7	25 model A	a 15
8	20 model B	f 90
9	20 model B	e 75
10	20 model B	d 60
11	20 model B	c 45
12	20 model B	b 30
13	20 model B	a 15
14	15 model C	f 90
15	15 model C	e 75
16	15 model C	d 60
17	15 model C	c 45
18	15 model C	b 30
19	15 model C	a 15
20	10 model D	f 90
21	10 model D	e 75
22	10 model D	d 60
23	10 model D	c 45
24	10 model D	b 30
25	10 model D	a 15

III. Result and Discussion

A. Effect Of The Fins On The Air Velocity Around The Pulley

The distribution of the air around the pulley in both models is described in Figure 9. It reveals that the air distribution is lower in the case of no fins model which causes a less convectional heat transfer between the pulley and the surrounding area. The convectional thermal coefficient of the pulley has a relation to the air speed and the temperature difference between the pulley and the surrounding. When the pulley is rotating at a constant speed, the magnitude of the turbulent flow remains unchanged as well as the convectional heat transfer coefficient. On the other hand, when the rotational speed of the pulley increases, the magnitude of the convectional heat transfer increases. In addition, air velocity increased three times when adding fins to the conventional model and running it at a constant speed.

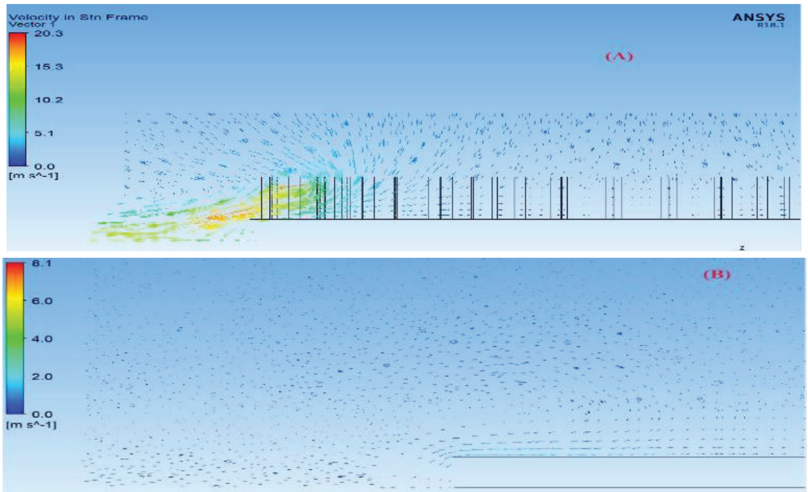


Figure 9: Air velocity for Model A (with fins) and B (without fins)

B. Effect Of The Number Of Fins And Their Orientation On The Air Velocity Around The Pulley

According to Figure 10 and 11, the relationship between the air velocity around the pulley with the number of fins and the fin angle, it has been noticed that the air velocity increases by increase the fins angle, it has shown that the maximum air velocity occurs at an angle of 90° and start decreasing when the fin angle decreases. Figure 10 shows when the fins angle increases 15°, the average air velocity is up by 2 m/s, and its notice that the number of fins does not have a large effect on the air velocity for all the models, but it has a great effect on the temperature as it will show later.

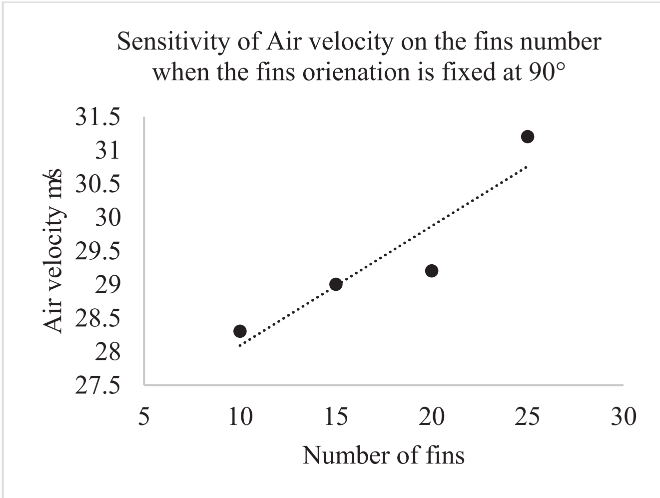


Figure 10: Sensitivity of the Air velocity on the fins number

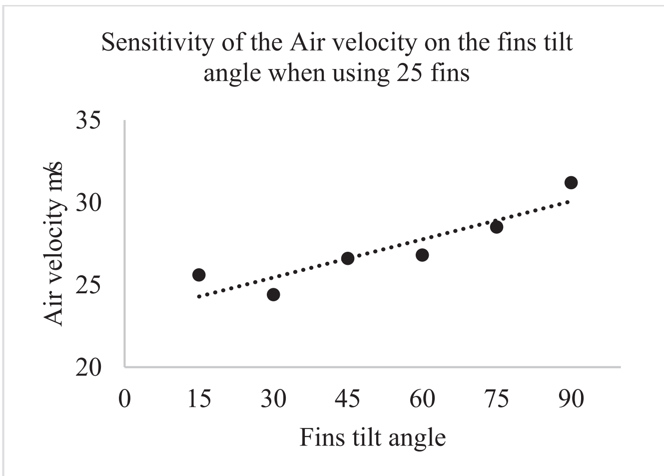


Figure 11: Sensitivity of the Air velocity on the fin orientation

C. Effect Of The Temperature

Figure 12 shows the distribution of the temperature generated in the pulley. Temperature generated in the pulley circumference is larger than the temperature generated in the middle. This could be explained by the effect of the direct contact between the belt and the pulley.

As shown in Figure 12, the distribution of the temperature for the pulley and the maximum temperature is located at the outer area of the pulley and the minimum temperature is at the inner (center) of the pulley, because the heat is generated at the outer area which is the region where the belt has frictional contact with the pulley and after adding the fins the temperature of the pulley were reduced from 70.7°C to 44.3°C, thus, the temperature of the belt is reduced as well. Therefore, the modification has made in this model is working, and the reduction in the temperature occurs because of the increasing in the overall convectional heat transfer due to the increasing of the air velocity by adding the fins.

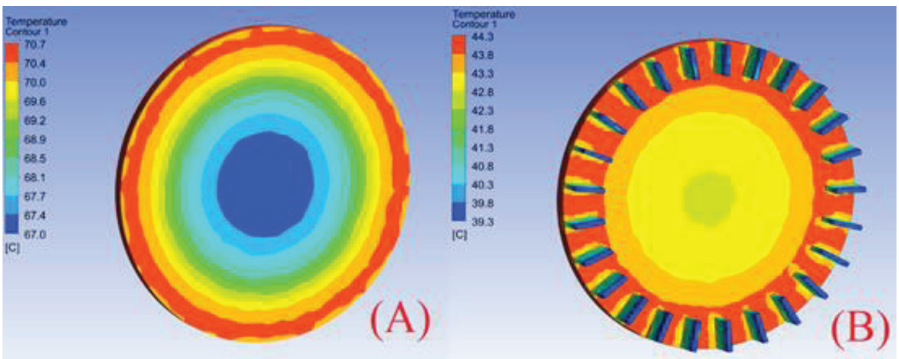


Figure 12: Magnitude of the Temperature on both Model Designs

D. Effect Of The Number Of Fins And Their Orientation On The Temperature Of The Pulley

Figures 13 and 14 show the relationship between the temperature of the pulley with the number of fins and fins angles, respectively, and it is noticed that by increasing the number of fins the temperature of the model decreases. Figure 13 shown that the minimum temperature of the pulley recorded at fins angle 90° and start increase when the fins angle decreases. We can notice that by increasing the number of the fins, a higher temperature reduction is recorded compared to fins angle. Therefore, it can be concluded that the number of fins play a bigger role in reduction of the temperature.

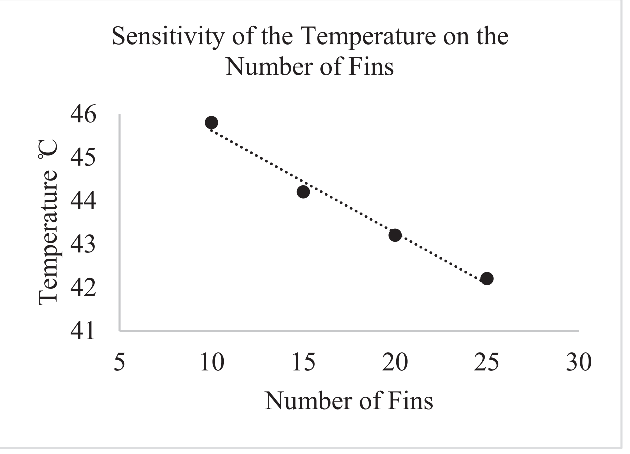


Figure 13: Sensitivity of the Temperature on the Fins Number

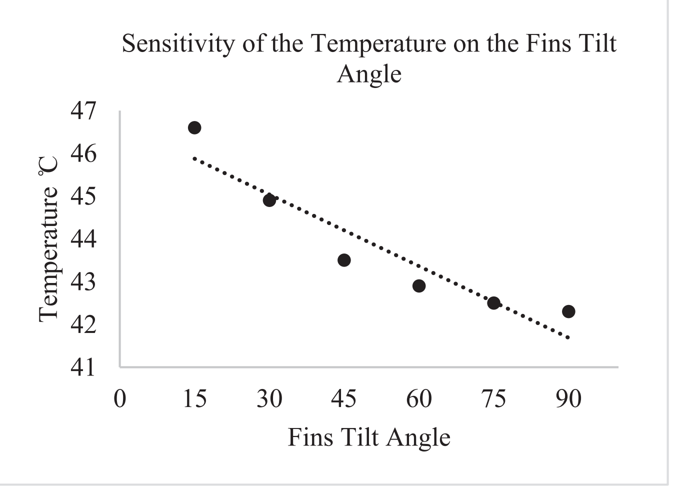


Figure 14: Sensitivity of the Temperature on the Fins Tilt Angle

E. Effect Of The Temperature On The Heat Flux

Figure 15 shows the temperature of the two models under the same operating condition with the same heat flux. It shows that the average difference of the temperature is around 20°C.

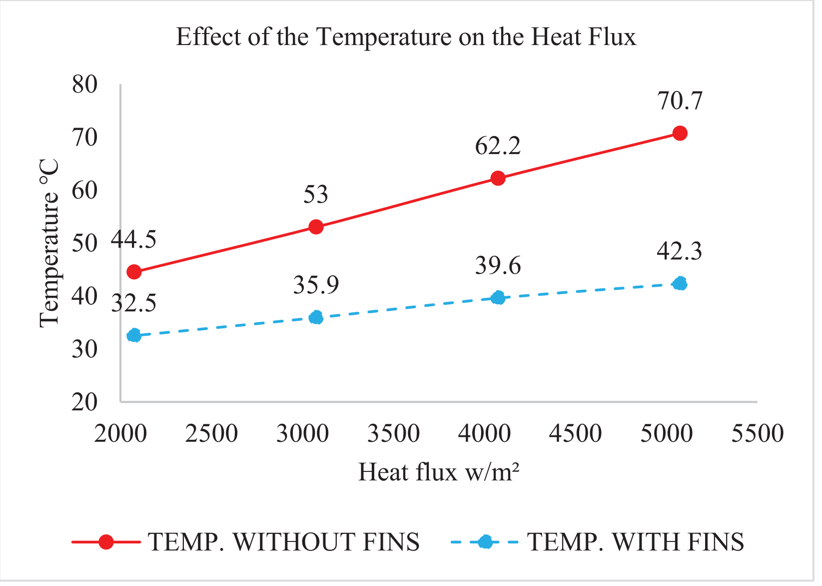


Figure 15: Sensitivity of the Temperature on the Heat Flux

IV. Conclusion and Recommendation

According to the simulations and examinations of the pulley, it has been recognized several key elements. After adding the cooling fins, the air velocity around the pulley has been increases and dropped in the temperature of the pulley due to increase in the total amount of the convectional heat transfer. It is because the changing of the heat transfer type from normal convection heat transfer to forced convection heat transfer by the fins.

After making the modification by adding the fins to the model, the velocity of air around the pulley increases for almost four times. The pulley convection heat transfer coefficient increases due to increasing in the air velocity. The average temperature of the pulley reduced by 23°C. After adding the cooling fins, it has been achieved the optimal working environment for the belt.

As it has been mentioned that if the temperature of the belt increases 10°, the lifetime of the belt will decrease by the half. Therefore, in the experiment the average belt temperature reduced by 18°C. Therefore, a double of a lifetime is expected to reach.

The air velocity changes by changing the vertical angles of the fins, when the fin angles increase 15°, the average air velocity drop by 2 m/s. The number of fins and the tilt angle plays a large rule in temperature reduction. The fin angle plays a large rule for air velocity compared to the number of fins.

As for recommendations, other shapes of the fins could be studied and the torque magnitude that they might support.

V. Acknowledgment

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VI. References

[1] Gárdonyi, L. Kátai, and I. Szabó, “Examination Of Drive Misalignment And V-Belt Temperature Conditions,” 2016.

[2] P. Kátai, L., Szabó, I., & Gárdonyi, “Az ékszíjtárcsa átmérők és az ékszíjak melegedési viszonyainak kapcsolata,” in *Fiatal Műszakiak Tudományos ülésszaka*, pp. 26-29, 2015.

[3] B. G. Gerbert, “Force And Slip Behaviour In V. Belt Drives,” 1972.

[4] T. F. Chen, D. W. Lee, and C. K. Sung, “An experimental study on transmission efficiency of a rubber V-belt CVT,” *Mech. Mach. Theory*, Vol. 33, No. 4, pp. 351-363, May 1998.

[5] H. Belofsky, “On the theory of power transmission by V-belts,” *Wear*, Vol. 39, No. 2, pp. 263-275, 1976.

[6] L. Bertini, L. Carmignani, and F. Frendo, “Analytical model for the power losses in rubber V-belt continuously variable transmission (CVT),” *Mech. Mach. Theory*, Vol. 78, pp. 289-306, 2014.

[7] L. Kátai, P. Szendrő, and P. Gárdonyi, “The power transmission stability and efficiency of V-belts,” *Prog. Agric. Eng. Sci.*, Vol. 12, No. 1, pp. 25-49, 2016.

[8] P. Gárdonyi, L. Kátai, and I. Szabó, “Examination of Drive Misalignment and V-Belt Temperature Conditions,” 2016.

[9] T. F. Chen and C. K. Sung, “Design considerations for improving transmission efficiency of the rubber V-belt CVT,” *Int. J. Veh. Des.*, Vol. 24, No. 4, pp. 320, 2000.

[10] C. Zhu, H. Liu, J. Tian, Q. Xiao, and X. Du, “Experimental investigation on the efficiency of the pulley-drive CVT,” *Int. J. Automot. Technol.*, Vol. 11, No. 2, pp. 257-261, 2010.

[11] F. H. Schafer, “Antriebsriemen.

Arntz Optibelt Gruppe Höxter, 2007," ISBN 978-3-00-0217113-5, 2007.
[12] W. D. Erickson, "Belt selection and application for engineers," Vol. 58. *CRC Press*, 1987.
[13] L. Della Pietra and F. Timpone, "Tension in a flat belt transmission: Experimental investigation," *Mech. Mach. Theory*, Vol. 70, pp. 129-156, 2013.
[14] F. Safranyik, A. Csatár, and A. Varga, "Experimental method for examination of state dependent friction," *Prog. Agric. Eng. Sci.*, Vol. 11, No. 1, pp. 29-42, 2015.
[15] X. Liu and K. Behdinan, "Analytical-numerical model for temperature prediction of a serpentine belt drive system," *Appl. Sci.*, Vol. 10, No. 8, 2020.
[16] D. S. Henningson and M. Berggren, "Fluid Dynamics: Theory and Computation," 2005.
[17] P. Wesseling, C. O. Computational and applied mathematics, and undefined 2001, "Geometric multigrid with applications to computational fluid dynamics," *Elsevier.*