KAUNAS UNIVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING & DESIGN

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COOLING UNIT FOR HYDRAULIC CYLINDER OF A ROWING EXERCISER

Final project for Master Degree

Supervisor
Prof. Dr. Vytautas Grigas

KAUNAS, 2017

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Mechanical Engineering & Design (621H30001)

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COOLING UNIT FOR HYDRULIC CYLINDER OF THE ROWING EXERCISER

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MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme MECHANICAL ENGINERING - 621H30001

Approved by the Dean's Order No.V25-11-20 of December 8th , 2016 y

Assigned to the student

Naresh Duppala
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1. Title of the Project

Cooling Unit for a Hydraulic Cylinder of the Rowing Exerciser

2. Aim of the project

To design a cooling unit for a rowing exerciser's hydraulic cylinder allowing to increase stability of resistance force generated by the cylinder during exercising.

3. Tasks of the project

1. Literature review. Problem statement, analysis of designs, regimes and principles of operation of the hydraulic cylinders. Analysis of heat transfer mechanisms, cooling systems, and their applicability for the rowing exerciser.

2. Modeling and analysis of thermal state of present design rowing exerciser's hydraulic cylinder. Determination of thermal loads acting the cylinder and excessive heat to be removed.

3. Design of rowing exerciser's hydraulic cylinder cooling system (several alternatives), numerical evaluation of their efficiency.

4. Specific Requirements

Cooling system should be autonomous (no need of external power supply). It should not increase significantly mass and size of rowing exerciser, be safe to use (ergonomic). Design of cooling system should allow its simple application on existing exercisers.

5. This task assignment is an integral part of the final project

6. Project submission deadline:

Task Assignment received	_ Naresh Duppala________	______________________
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Supervisor	Dr. Vytautas Grigas________	______________________
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SUMMARY

Rowing is one of best kinds of exercises having a great impact on sportspersons physical condition, including muscle strength and endurance. There are several types of rowing machines available and hydraulic rowing machine is one of most efficient kind keeping in mind its budget, compactness and reliability. Hydraulic cylinders connected to the levers imitating oar handles are used in such machines to generate the resistance force during exercising. This force is proportional to the speed of cylinder compression/extension (their piston insertion/extraction) in turn depending on intensity of exercising. Mechanical energy of the athlete applied on the cylinder during exercising is converted to the thermal energy of the cylinder, so it tends to heat after certain period of continuous functioning, then the viscosity of fluid circulating in the cylinder and correspondingly resistance force decrease.

The aim of this master’s thesis is to improve the performance of a hydraulic cylinder of the lever type rowing machine by improving its cooling rate. Therefore the analysis of design, regimes and principles of operation of the hydraulic cylinders, heat transfer mechanisms and cooling systems was carried out. The thermal loads acting the present design cylinder of rowing exerciser and excessive heat to be dissipated were determined by computational analysis of its thermal state. Two types of cooling devices (having longitudinal and circular cooling fins) mounted onto the cylinder and increasing the rate of heat transfer to the environment by increasing convection were designed and their efficiency was evaluated by means of numerical simulation.

Keywords: rowing machine, hydraulic cylinder, resistance force, computational analysis, thermal state, convection, cooling fins.

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SANTRAUKA

Irklavimas yra viena iš sporto šakų, turinčių visapusiškiausią įtaką sportininkų fizinei būklei, nes leidžia lavinti tiek praktiškai visų raumenų jėgą, tiek ir ištvermę. Yra įvairių tipų irklavimo treniruoklių, o vieni plačiausiai naudojamų yra gana paprasti, patikimi, kompaktiški ir nebrangūs svirtiniai treniruokliai, kuriuose apkrova generuojama hidraulinio cilindro tipo įrenginiais. Tokių hidraulinių cilindrų sudaroma pasipriešinimo jėga yra proporcinga jų stūmoklio įstūmimo/ištraukimo greičiui, savo ruožtu priklausančiam nuo mankštinimosi intensyvumo, t.y. irklų rankenas imituojančių svirčių, prie kurių prijungti cilindrai stūmimo/traukimo greičio. Mankštinantis tokiais treniruokliais sportininkų mechaninė energija virsta cilindro ir jame cirkuliuojančio hidraulinio skysčio šilumine energija, todėl treniruotės metu cilindras įkaista, hidraulinio skysčio klampa ir atitinkamai jo generuojama pasipriešinimo jėga sumažėja.

Šio magistro darbo tikslas yra pagerinti svirtinio irklavimo treniruoklio hidraulinio cilindro efektyvumą pagerinant jo aušinimą. Išanalizavus hidraulinių cilindrų konstrukcijas, veikimo principus, šilumos perdavimo mechanizmus ir aušinimo sistemas ir nustačius esamos konstrukcijos cilindrą veikiančias šilumines apkrovas bei išsklaidytiną šilumos kiekį sukurti dviejų tipų cilindro aušinimo įtaisai (turintys išilgines ir žiedinės aušinimo briaunas), kuriuos sumontavus ant cilindro padidinamas šilumos perdavimo į aplinką efektyvumas padidinant konvekcijos proceso efektyvumą. Įtaisų efektyvumas įvertintas atliekant jų šiluminio būvio analizę skaitiniais metodais.

Reikšminiai žodžiai: irklavimo treniruoklis, hidraulinis cilindras, pasipriešinimo jėga, skaičiuojamoji analizė, šiluminis būvis, konvekcija, aušinimo briaunos.

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Introduction

Increasing interest of mankind towards physical training resulted in the advancement of technology in physical training equipment. Especially for the athletes and sports persons, a lot of technical improvements ensuring high quality, reliability, and functionality of various exercising machines have been made.

Rowing simulator is one of the most popular universal training devices which have significant effect on improving the muscular strength and endurance of the athletes. Such simulators are especially designed to give an experience of real time rowing to the users. Considering the Rowing as an exercise, it is mild enough to meet the needs of cardiac patients and vigorous enough to match the mettle of world-class athletes [2].

There are several types of rowing machines and the rowing exercisers with adjustable linear stroke Hydraulic cylinders (dampers) are one of them. They generate resistance on levers imitating oars handles proportional to the speed of cylinder compression/extension (piston extraction/compression) which is directly related to the intensity of exercising. In addition to several advantages (price, compactness, reliability etc.) they have a fairly significant shortfall: the resistance force generated by such devices at certain intensity of exercising drops with respect to the increment of temperature inside the cylinder which causes reduction of the viscosity of hydraulic fluid circulating in it [3].

The objective of this research is to design cooling unit for a rowing exerciser hydraulic cylinder which would increase stability of resistance force generated by the cylinder by improving its cooling efficiency thus preventing growth of the cylinder temperature and corresponding reduction of hydraulic fluid viscosity during the exercising process. The following tasks were specified to serve this purpose:

- Analysis of designs, regimes, and principles of operation of the hydraulic cylinders;
- Analysis of heat transfer mechanisms, cooling systems, and their applicability for the rowing exercisers;
- Analysis of thermal state of present design of rowing exerciser's hydraulic cylinder; determination of thermal loads acting the cylinder and excessive heat to be removed;
- Design of cooling unit for hydraulic cylinder of rowing exerciser (several alternatives) and evaluation of their efficiency by means of numerical simulation.

The problem is solved by achieving better heat dissipation due to increasing efficiency of convection by the enlargement of surface area of the hydraulic cylinder by additional fins.

1 Literature Review

Theoretical background

This literature review has different kinds of sections which relates to the background of several types of rowing machines. First chapter is an overview of hydraulic cylinder and its construction. In the second chapter discussion is made on surface fins and its types with respect to the working efficiency. Final section of the review consists of thermal properties and their applications in this research work.

1.1 Rowing machines

A Rowing simulator or rowing machine is used to serve the purpose of indoor physical fitness training. This machine simulates the action of watercraft rowing which is correlated in order to measure the amount of energy used by the rower using the machine. The construction of the simulator helps in simulating the training in the form of a rowing sport.

Construction of a rowing simulator

Rowing simulators design consists of several components, Energy damper or breaking mechanism is a hydraulic damper which is used to provide resistance. Energy damper is connected with a Chain/ Handle which gives support as it works as a connecting rod to a hydraulic cylinder. A foot rest or stretcher is used where the rower places their feet, works with a sliding mechanism is attached to the same surface as the damper [6]. There are different types of damping mechanisms with a variety of rowing machine layouts. All mechanisms have their own advantages and disadvantages which are considered in this research.

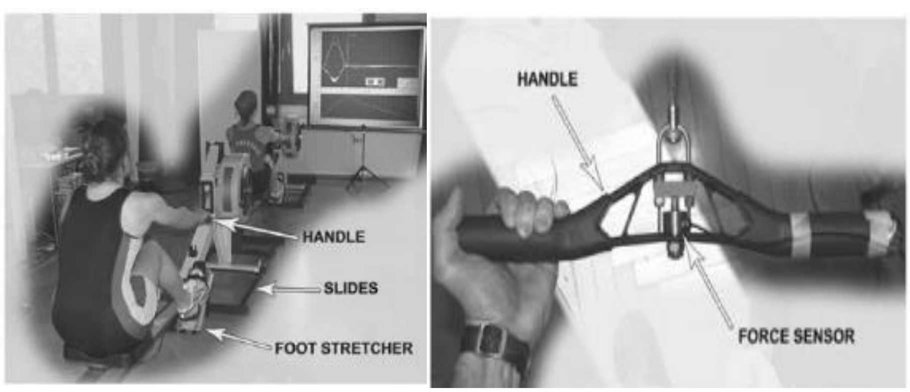

Figure 1: Components of a rowing machine a) Handle, Slides & a Foot stretcher b) Handle with a force sensor [4]

Rowing machines consists of a digital display which calculates the rower's power by measuring the stroking process with respect to flywheel speed and recording the rate of recovery deceleration. The computer then calculates the parameters such as speed, power, distance covered and energy usage with the known moment of inertia of the rowing flywheel. The data can also be transferred using software and then further be analyzed.

1.2 Types of rowing simulators

There are mainly three designs which allow the feet stretcher which is connected to flywheel and handle to move in back and forth motion relatively nearer and apart from each other. The first one is with the fixed foot stretcher and flywheel, only the sliding of seat is analogous on rail. The second one is with both foot stretcher and seat slide over a rail. The analogous movement of seat and flywheel are the result of rower moving at average speed. The third one is with the fixed seat where the foot stretcher slides backward away from rower.

As per the resistance mechanism used in the construction of a rowing machine, they are classified as follows:

1.2.1 Air type rowing simulator

These type of rowing machines are one of the popular among the available ones. These are first introduced into market around 1980s and many considered them as the best at the time of their introduction [5]. Air resistance simulators use a fanlike air fins for generating resistance on the flywheel with the help of flywheel braking. The energy dissipated is calculated by the moment of inertia of the flywheel. An air type rowing machine works with the help of resistance created by an internal fly wheel and resistance will be created by the air flow over fly wheel. Rower will perform the training by gripping the rowing handle. This rowing handle will be connected to the flywheel using a chain. So, user pulls the chain with support of handle making the flywheel spin. The faster the rower pulls the chain, faster the flywheel will spin through the air creating a greater resistance. Additional dampers can be used for altering the air flow, further creating a change in the feel of stroke. Air resistance simulators are often used during the offseason weather by the competitive sport rowers.

Figure 2 Air type rowing Machine [1]

Advantages and Disadvantages

Air rowing simulators have natural movement and smooth action as they result in continuous and smooth resistance of the air brakes. Less wear and tear of the mechanism can be easily attained as the machines are less bulky and easier to use on regular bases. They are most preferred because the resistance is automatically adjusted as per the stroke rate with full range of movement including full extension of both arms and legs [7].

On the other hand, there is a downside of air rowing simulator which consists of the machine being more expensive due to the expensive frame and moving parts. Air rowing machines are the noisiest for the indoor usage because of the whooshing sound of air flow over the fins and dampers.

1.2.2 Water rowing machines

These type of rowing machines are one of the newly introduced technologies into the world of physical training equipment. Many users who prefers smooth and quiet operation of the rowing machine prefers to work on this kind. These models consist of revolving paddle in an enclosed tank of water. The resistance in this rower is created by the mass and drag of the moving water. These type of rowing machines helps in burning the calories by providing required resistance to the movement of the sliding seat.

Functioning of the water resistance rowing simulator is hard to copy the action of a scull on water but the mechanics of spinning flywheel comes close compared on dry land as water is denser than air therefore there is no need for any extra resistance or dampening. A water type rowing machine mainly consists of paddles (water flywheel), a tank of water and a connecting chain with handles. Pulling the handle provides required motion to the paddles in water tank making them to revolve inside the water.

The mass of moving water collected around the paddles helps in creating drag against the paddles of rowing machine. Thus, drag helps in producing the required resistance to the user. The greater the drag, the more will be the resistance offered to the user. In addition, 'WHOOSH' sound made by the water tank while rowing gives real time experience to the user.

Figure 3: Water type rowing machine [8]

Advantages and Disadvantages

Water rowing simulators have smooth operation of rowing machine offers consistent resistance throughout the strokes offered by the user as there is no virtual delay in the resistance at the beginning of the pull but gradually the resistance drops during middle strokes as the water is lifted away from the blades. They come with low maintenance cost and less noisy compares to other variants.

On the other hand, Storage comes as a disadvantage because it occupies a greater floor space and purchase price of such water rower simulators are comparatively higher due to the technology used. Water needs to be changed occasionally in order to have a longer life of machine and better working [9].

1.2.3 Magnetic rowing machines

Magnetic rowing machines are most popular among the domestic rowing machines which are in use. Their unique resistance mechanism made them the quietest of all the available variants. A magnetic rowing machine resists the efforts of user to move handle and seat thus, providing the user with workout for muscles and cardiovascular system. Magnetic resistance models control the resistance by electromagnets that engage the flywheel mechanical braking system which is adjustable and energy can be measured successfully by the rower.

Figure 4: Magnetic type rowing cylinder [11]

A magnetic type rowing machine consists of strong magnets, a spinning flywheel, a handle, and a chain connecting them both. This rower works by varying distance between magnets and flywheel which spins away from the magnet as the user pulls the handle. Further, resistance levels can be adjusted using mechanical slides. This type of rowing simulator uses electromagnets to provide resistance which is used for braking and the magnets slowdown the main flywheel resulting in the momentum support for the rower.

Advantages and Disadvantages

The magnetic rowing simulators are very quiet in operation when compared to rest of the simulators especially some are almost silent. One of the main advantage of this kind is that there is a wide range of resistance levels acquired due to magnetic brake which generates resistance [10]. The storage uses less space than the air or water rower simulators. Little maintenance is required.

On the other hand, the drawback of magnetic rowing simulator is that the resistance is constant, rowers using air and water resistance simulators are more accurate to actual rowing whereas in this kind the resistance increases the harder the handle is pulled as they use electromagnets to build the resistance.

1.2.4 Hydraulic rowing machines

Hydraulic rowing simulators come with two major benefits being low price and smaller as well as quieter than any of the rowing simulators available. Hydraulic rowing machines uses piston resistance which comes from hydraulic cylinder that are usually attached to handles of rowers. The handle is adjustable and is able to fix the trajectory that handles the stroke and return. Furthermore, in this kind of machine the seat is in fixed position that helps to eliminate the leg drive.

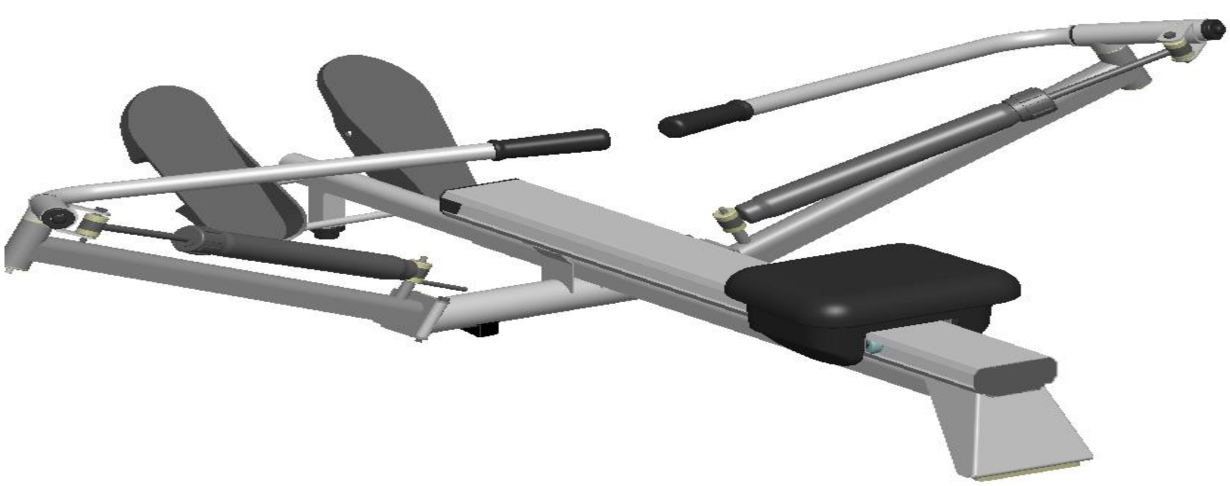

Figure 5: Hydraulic type rowing machine [12]

Hydraulic rowing simulators uses the applied force at one point for the transferring of that power to another point through fluid. In piston rowing machines, hydraulic cylinders are attached to the handle which helps to exert force on the handle by pulling them back which helps in providing resistance of air or fluid in the cylinders [3].

Advantages and Disadvantages

There are several advantages that make hydraulic rowing simulators excellent as it is a simple machine with a lower price cost compared to rest machines. Hydraulic simulators are small in size and can be easily folded for storage purposes. Noise friendly and they offer variable resistance by adjusting the fluid in cylinders.

On the other hand, these rowing simulators have some drawbacks with a piston machine as most models do not provide smooth rowing action as compared to other resistances such as magnetic or water rowing simulators. Resistance levels change as oil inside heats up making hydraulic rowing simulators fail to emulate real conditions.

Considering the facts that hydraulic cylinders create smoother operational experience to the users with its quiet operation and compactness.

1.3 Hydraulic cylinder

Hydraulic cylinders are also known as linear hydraulic motor which is a mechanical actuator. Hydraulic cylinder converts fluid power to mechanical power, and are used to give a unidirectional force through a unidirectional stroke. They are well known as JACKS or RAMS[13]. These cylinders are used to high pressures and are responsible for producing large forces with precise movement. Hydraulic cylinders are made of strong materials such as steel and are designed in order to withstand larger forces.

Classification of Hydraulic cylinders

Standard Hydraulic cylinders are designed to meet the wide range of applications and specifications. The following types of cylinders provides the overview classification:

Single acting cylinder

Single acting cylinder will take power-stroke solely in single direction. That is either it can develop necessary force in forward stroke of cylinder or backward stroke of cylinder, reckoning on its construction. The non-productive direction of cylinder stroke is achieved by varied means that such as self-weight (gravity), spring, auxiliary cylinder etc. [14]. These can simply be termed as single acting cylinders as they work in uni-direction which results forces in a single direction.

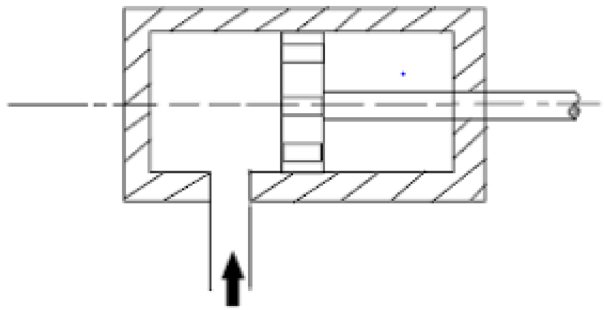

Figure 6: Single acting cylinder

Double acting cylinder

A double acting cylinder is considered to be more common than the single acting cylinder. In a double-acting cylinder, working fluid acts simultaneously on the both sides of the piston. Retraction and extension of the piston is achieved at each end of the port which is supplied with hydraulic fluid[14]. It is used for retraction of the piston where an external force is not available or where a high force is required.

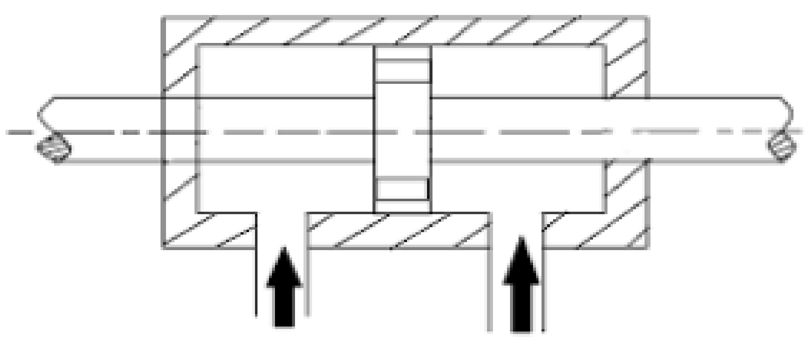

Figure 7: Double acting cylinder

Working principle

Hydraulic cylinder gets its power from incompressible fluids, which is typically oil or water. These hydraulic fluids are used to transmit forces from one location to another. Most breaking systems work based on hydraulics. The working principle of a hydraulic system is framed by Blaise Pascal which states as "Pressure applied to any part of a confined fluid transmits to every other part with no loss[15]. The pressure acts with equal force on all equal areas of the confining walls and perpendicular to the walls". Therefore it can be said that any change in applied pressure at a given point of the fluid is transmitted throughout the fluid.

1.4 Nomenclature of Hydraulic cylinder

A hydraulic cylinder consists of the following parts as mentioned below:

A hydraulic cylinder consists of cylinder barrel which is made from a transparent tube and its function is to hold the pressure of cylinder. Cylinder base or cap is attached to the body of cylinder and its function is to enclose the pressure at the one end of the cylinder. The size of the cap is determined by its bending stress.

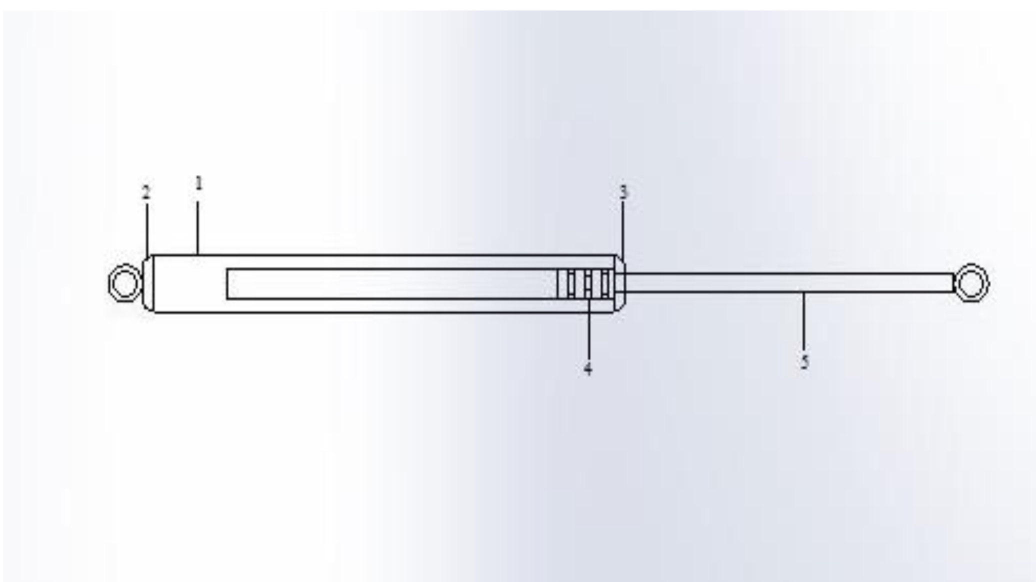

Figure 8: Schematic diagram of hydraulic cylinder

(1) Cylinder barrel (3) Cylinder head (5) Piston Rod

(2) Cylinder base or cap (4) Piston

Cylinder head seals the rod and barrel together and its main function is similar to the cap as it encloses the pressure chamber from the other end of the barrel. Piston is used to separate the pressure zones inside the cylinder's barrel using seals which can be either single acting or double acting. The difference in pressure zones inside the barrel is due to the retraction and extension of cylinder between two sides of piston. The piston is attached to the piston rod which is typically made of steel and extends from barrel through the rod head. The piston rod is also responsible for connecting the hydraulic actuator to the active machine component.

1.5 Operation of a hydraulic cylinder

Hydraulic cylinders are used to convert fluid power into mechanical motion which consists of a cylindrical body that is connected to piston and piston rod which moves in a back and forth motion, closures at each end with the help of cap and head where the rod comes out of the cylinder, movable piston and a rod attached to a piston.

A hydraulic cylinder is actuator of the system, when fluid pressure acts on the piston. The piston rod is transmitted by the fluid pressure resulting in a linear motion [17]. If an assumption is made that the fluid enters from the cap end during extension stroke and the fluid pressure in the rod/head is zero than the force developed by the fluid pressure acting on the piston is calculated by multiplying the cylinder pressure and piston area.

1.6 Loading of a Hydraulic cylinder

Loading of cylinder depends upon the type of its application.

Sliding load

Cylinders can be used to move high friction sliding loads. Some examples of this are machine slides, pallet shuttle systems on automated machinery, milling machine tables, and grinder tables [18]. Unit weight, lubrication and required speed should be considered when sizing a cylinder for a sliding load application.

Vertical lifting

Cylinders must be sized in order to have more space then needed to balance the load and to obtain a lift. The faster lift is attained when the cylinder is oversized but in the case of hydraulic cylinders, this is not true [18]. By increasing the air pressure, the cylinder has an upward force to start the vertical motion of the load.

Rolling load

Cylinders can be used to move rolling loads and loads which can be moved on low friction bearings. The cylinder must have a thrust force capable of moving a load which is equal to one tenth of the actual load. Prevention of momentum of the load from damaging either cylinder or machine can be achieved by deceleration of cylinder stroke when using a cylinder to move a rolling load [20].

1.7 Hydraulic fluid

Hydraulic fluids play a vital role in the study of Hydraulic systems. Hydraulic fluid is also known as hydraulic liquid which is the medium by which the power is transferred in the system or the machinery. Hydraulic cylinders will work most efficiently if the hydraulic fluid used has zero compressibility.

Types of hydraulic fluids

The hydraulic fluid is classified according to their source of availability and purpose of use [19]:

a) **Petroleum based/Mineral based:** Mineral or petroleum based hydraulic fluids have oil base and they are responsible for high performance at lower cost. They are further classified as the fluids which do not have additives, fluids which contain oxidants and help the system to be protected from any kind of contamination and finally the fluids which have anti wear additives.
b) **Water based/Fire resistant:** The water based or fire resistant hydraulic fluids are mainly used in industries where there is a chance of any hazards. These fluids generate less heat when burnt than those of mineral/petroleum based fluids. These fluids are classified as soluble oils, water based, invert emulsions, water glycols, phosphate and polyol esters.
c) **Synthetic fluids/Man made fluids:** Synthetic fluids are artificial made as they are named Man made fluids using raw materials synthesized by chemically modified components or crude oil.

1.7.1 Hydraulic fluid properties

Hydraulic fluid is selected on basis of its fluid properties and its effect on the hydraulic system. Hydraulic fluids have many properties as shown below [23]:

a) **Viscosity:** One of the main property of hydraulic fluid is viscosity which measures the resistance of flow of fluid that is inversely proportional to its fluidity. There are two different types of units for viscosity, dynamic or absolute and kinematic viscosities of hydraulic fluids.

b) **Viscosity index:** Viscosity index is a unit less value which indicates the temperature range within the used fluid. The higher the index better is the stability of viscosity of fluid. If the viscosity index of the fluid is high, the viscosity of fluid becomes very low at high temperatures and vice versa.
c) **Bulk modulus:** Bulk modulus is substance resistance to uniform compression, in simple words that means change in volume by change in pressure. High bulk modulus is useful for high transmissions and low power losses. The low modulus is damping material for hydraulic system.
d) **Wear resistance:** Hydraulic fluid should prevent the inner walls of the cylinder and piston surface from wear in long run.

There are several characteristics of hydraulic fluid which consists of lubrication of the system, fluids are corrosion resistive, Hydraulic fluids remove impurities and abrasive elements from the system, they are used in the process of transferring the hydraulic energy, and Heat dissipation is achieved easily in the hydraulic system. Depending upon the above mentioned factors, duty of the hydraulic fluid will be determined which are classified as high level, medium level, and low level duties.

2 Thermal study properties

Generally, there are three possible case of heat to get transferred: Conduction, Convection, and Radiation.

2.1 Heat transfer by convection

Convection heat transfer is the thermal energy transfer from one place to other by the fluids movement. Convection is typically the dominant variety of heat transfer in liquids and gases [21]. Convective heat transfer involves the combined process of physical phenomenon and temperature change.

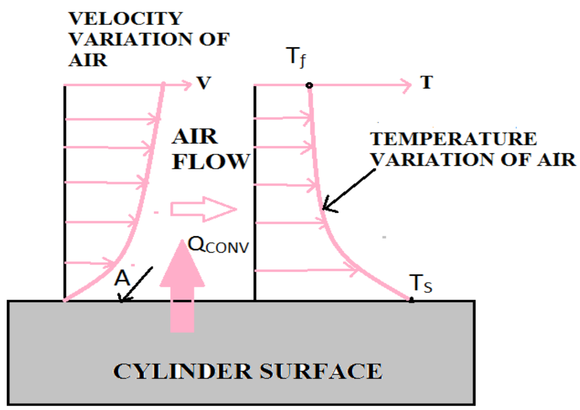

Figure 9: Heat convection through air flow

The term convection will generally term to transfer of heat with any fluid movement, however temperature change is defined for the term of transfer due solely to bulk fluid flow. Though usually mentioned as a definite technique of heat transfer, convection describes the combined effects of physical phenomenon and fluid flow or mass exchange.

There are two types of convective heat transfer:

Free or natural convection

Fluid motion is caused by buoyancy force that results in the density variations owing to variations of thermal temperature within the fluid. This is often referred to as Natural convection. Within the absence of associate degree external supply, once the fluid is to bear with a hot surface, its molecules separate and scatter, inflicting the fluid to be less dense when compared [22]. As a consequence, the fluid is displaced whereas the cooler fluid gets denser and therefore the fluid sinks. Thus, the warmer volume transfers heat towards the cooler volume of that fluid.

Forced Convection

In forced convection, a fluid is forced to flow over the surface by associate external supply like fans, by stirring, and pumps, by making associate unnaturally evoked convection current [24].

2.2 Heat transfer through extended surfaces (Fins)

Overheating of cylinder can be reduced by increasing the rate of heat transfer and this will be possible either by increasing the coefficient of convection heat transfer (h_c) or by increasing the surface area through which heat is to be transferred.

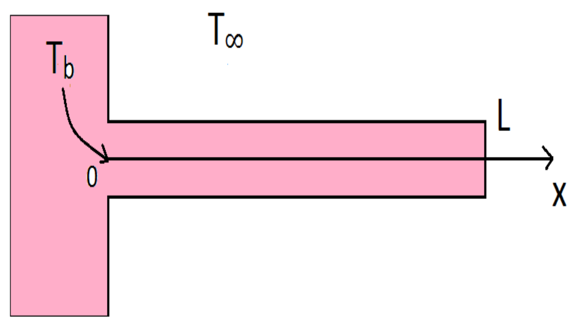

Figure 10: Extended surface from base (Tb-Base temperature, T_∞-Ambient temperature)

A fan or a pump is required for increasing the coefficient of convection heat transfer or in some cases it may require to install a larger cylinder in place of existing cylinder. Whereas increasing of surface area requires extending of surface by attaching fins either longitudinal or radial.

Types of fins

For a cylindrical surface, there are two possible types of fins to attach for increasing its surface area.

a) **Longitudinal Fins:** These are rectangular surfaces with uniform cross sectional area attached around the cylinder surface with uniform spacing. Longitudinal fins with cross sectional shape of tapered runs all along the length of the cylinder. Generally, materials with high conduction like aluminum, copper and steel are used as fin material [26].

Longitudinal fins on the cylinder helps in the application where the flow on the cylinder is expected to be stream lined along the cylinder length. Heat transfer coefficients vary with change in the cross-sectional geometry and dimensions of the fin.

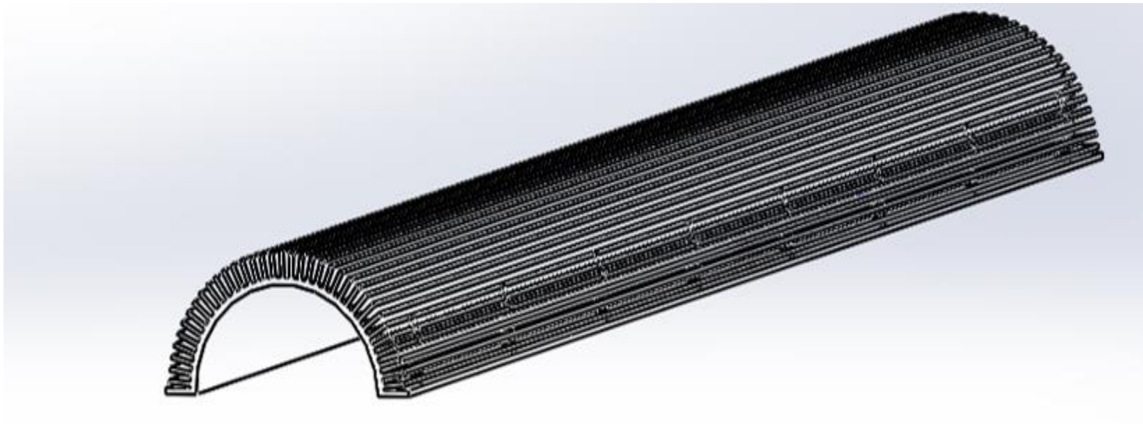

Figure 11: Longitudinal Fins

b) **Radial Fins:** These are disc shaped surfaces with uniform cross sectional area attached around the cylinder surface with uniform spacing. Radial fins with cross sectional shape of tapered runs all along the height of the cylinder. Generally, materials with high conduction like aluminum, copper and steel are used as fin material [27].

Radial fins on the cylinder helps in the application where the flow on the cylinder is expected to be turbulent over the cylinder length. Heat transfer coefficients vary with change in the cross-sectional geometry and convexity of the fin.

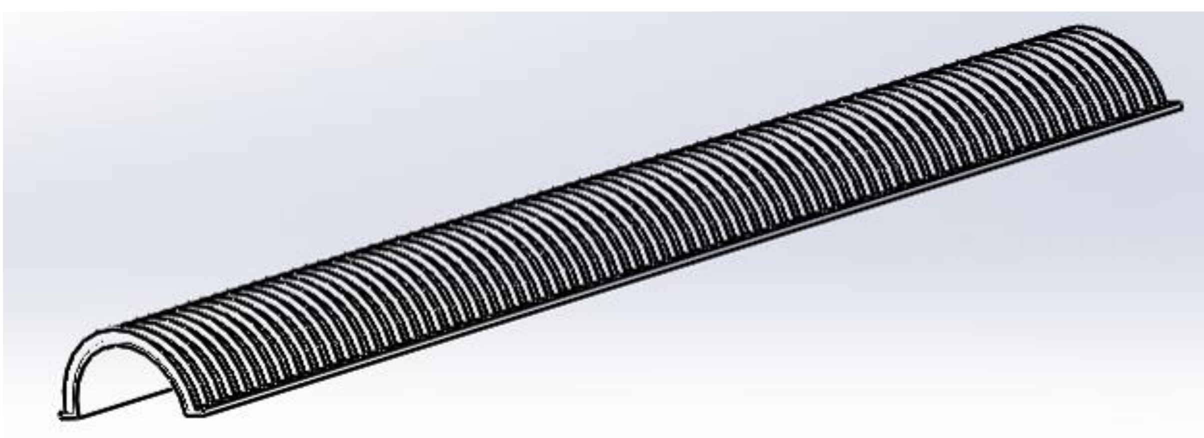

Figure 12: Radial Fins

3 Theoretical Calculations

Using the measured dimensions of the hydraulic cylinder, loads acting on the cylinder and volume capacities of the cylinder are calculated and presented below. Thermal loads acting on the cylinder and the amount of heat required to be dissipated from the cylinder surface is calculated and presented below.

3.1 Geometrical calculations of hydraulic cylinders

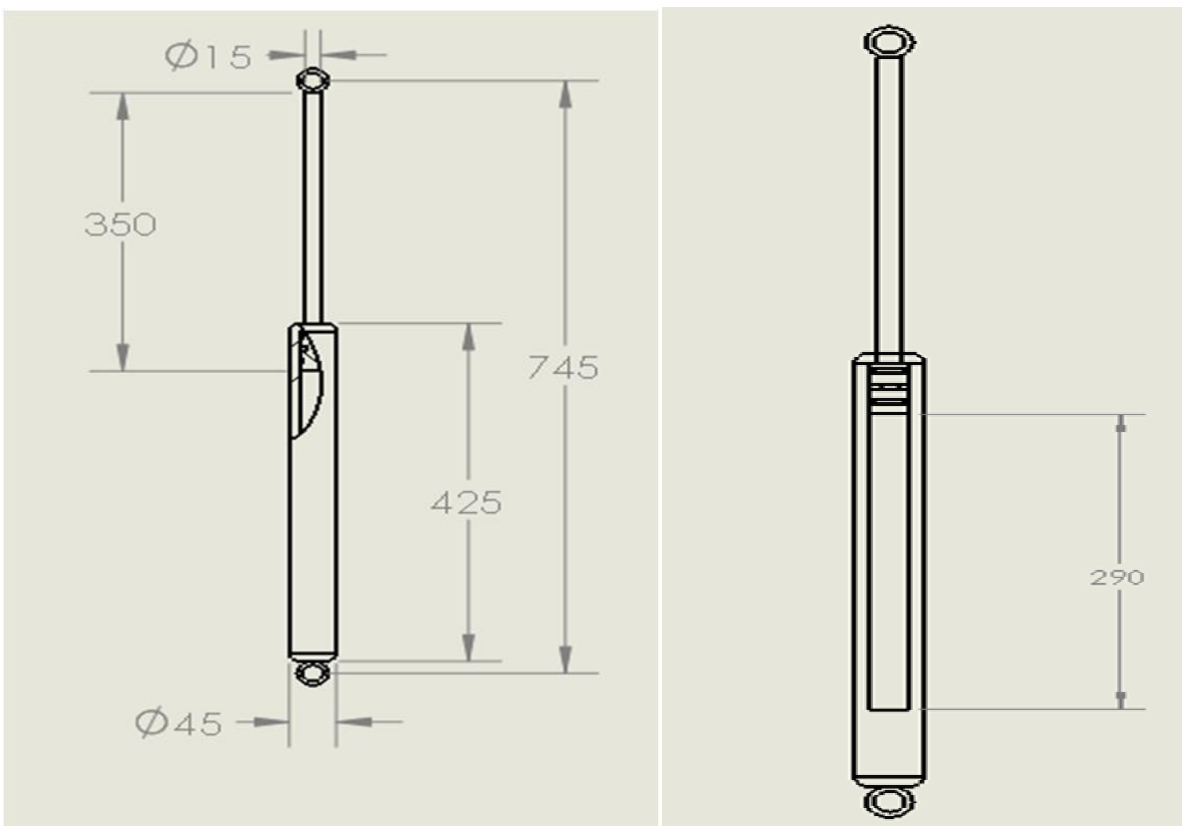

Figure 13: Schematic diagram of cylinder assembly

Dimensions of the cylinder with which

a) Diameter of the cylinder (D_C) = 45mm
b) Total length of the cylinder (L_C)= 425mm
c) Diameter of the Piston rod (d_1) = 15mm
d) Diameter of piston (d_2) = 25mm
e) Total length of the Piston rod = 350mm
f) Stroke length (L_S) = 290mm

g) Mass of the entire assembly = 1600g

Blind end area of cylinder $= \pi * (radius\ of\ cylinder)^2$
= 1590mm^2

Rod end area of cylinder = (Blind end area) – (area of rod)

Area of piston rod $= \pi(radius\ of\ rod)^2$

= 190mm^2

Therefore, rod end area of cylinder = 1400mm^2

Effective area of the cylinder = 325mm^2

Total surface area of cylinder = $2\pi Rh + 2\pi rh + 2(\pi R^2 - \pi r^2)$

= 90000mm^2

Volume capacity of the cylinder should be calculated at two positions of the piston rod:

a) Cylinder volume capacity of fluid when in extended position = 150ml

b) Cylinder volume capacity of fluid when in retracted position = 100ml

Force (N) and Pressure (Pa):

In this case, hydraulic cylinder is designed for offering different resistance to the user as per the user's requirements the load applied on cylinder may vary and for calculation purpose 4 different cases are taken into consideration and they are 30kgs, 40kgs, 50kgs and 60kgs respectively.

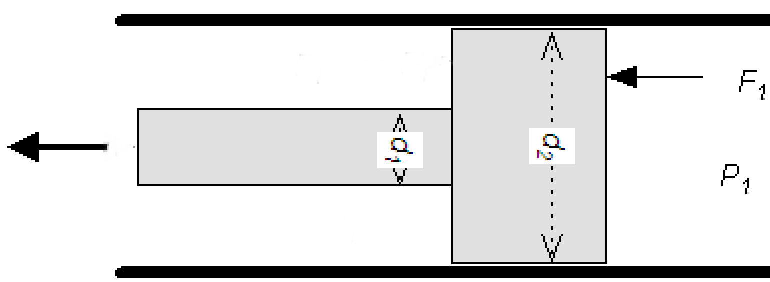

Figure 14: Forces acting on Piston

F_1 is extending force; d_1 is diameter of the rod; d_2 is diameter of piston

P1 is pressure acting on piston rod both ways while retracting and extending respectively [29].

From the construction of the training equipment calculated Forces (F_1) required for extending the cylinder are shown in below table. Based on the Force; the pressure generated on the walls of the piston can be calculated.

$$\text{Pressure (Pa)} = \frac{F1}{Area\ of\ piston\ bore}$$

Table 1: Loads acting on hydraulic cylinder

Load applied (Kgs)	Force (N)	Pressure($x10^5$Pa)
30	530	11.6
40	710	15.6
50	880	19.3
60	1070	23.4

3.2 Thermal calculations

Heat convection

Heat convection is termed as heat energy transferred between a surface and a moving fluid at different temperatures [28]. Convection is a combination of diffusion and bulk motion of molecules. Velocity of the fluid is low near to the surface of cylinder and it increases as it moves away from the cylinder's surface whereas, diffusion of heat is high near the surface of cylinder and decreases on moving away from the cylinder's surface.

For calculating the heat convection:

$$Q = Hc * A * dT \tag{3.1}$$

Q is heat convection in Watts

H_c is coefficient of heat convection in ($W/m^2 * °C$)

A is total surface area in m^2

dT is temperature difference between surface in contact and fluid in °C

Steps for calculating Maximum allowable temperature:

a) Convection heat coefficients considered for achieving the maximum possible temperature at which the hydraulic cylinder can work without failure are 20, 30, 50 and 75 ($W/m^2 * °C$)
b) Heat power generated inside the cylinder is 40W.
c) 'dT' is the difference between surface temperature and bulk ambient temperature in °C

$$dT = (T_s - T_a)$$

d) Surface Area of the cylinder's faces where convection of heat is applicable:

$$A = \pi * (0.0125) * (0.250) \quad = 0.01\, m^2$$

Case 1:

Q=40W, H_c =20($W/m^2 * °C$), A=0.01 m^2, T_a= 27°C

At the above stated conditions surface temperature of cylinder is T_S = 161°C

Case 2:

Q=40W, H_c =30($W/m^2 * °C$), A=0.01 m^2, T_a= $27^{°C}$

At the above stated conditions surface temperature of cylinder is T_S = 135°C

Case 3:

Q=40W, H_c =50($W/m^2 * °C$), A=0.01 m^2, T_a= 27°C

At the above stated conditions surface temperature of cylinder is T_S = 107°C

Case 4:

Q=40W, H_c =75($W/m^2 * °C$), A=0.01 m^2, T_a= 27°C

At the above stated conditions surface temperature of cylinder is T_S = 80°C

Comparing theoretical and FEA results

Theoretical results table:

Table 2: Calculated surface temperature of hydraulic cylinder at different h_c

Heat convection coefficient ($W/m^2 * °C$)	**Surface temperature(°C)**
20	161
30	135
50	107
75	80

FEA results table:

Table 3: FEA results of cylinder’s surface temperature at different h_c

Heat convection coefficient (W/m² * °C)	**Surface temperature(°C)**
20	166
30	131
50	101
75	84

Graphical comparison

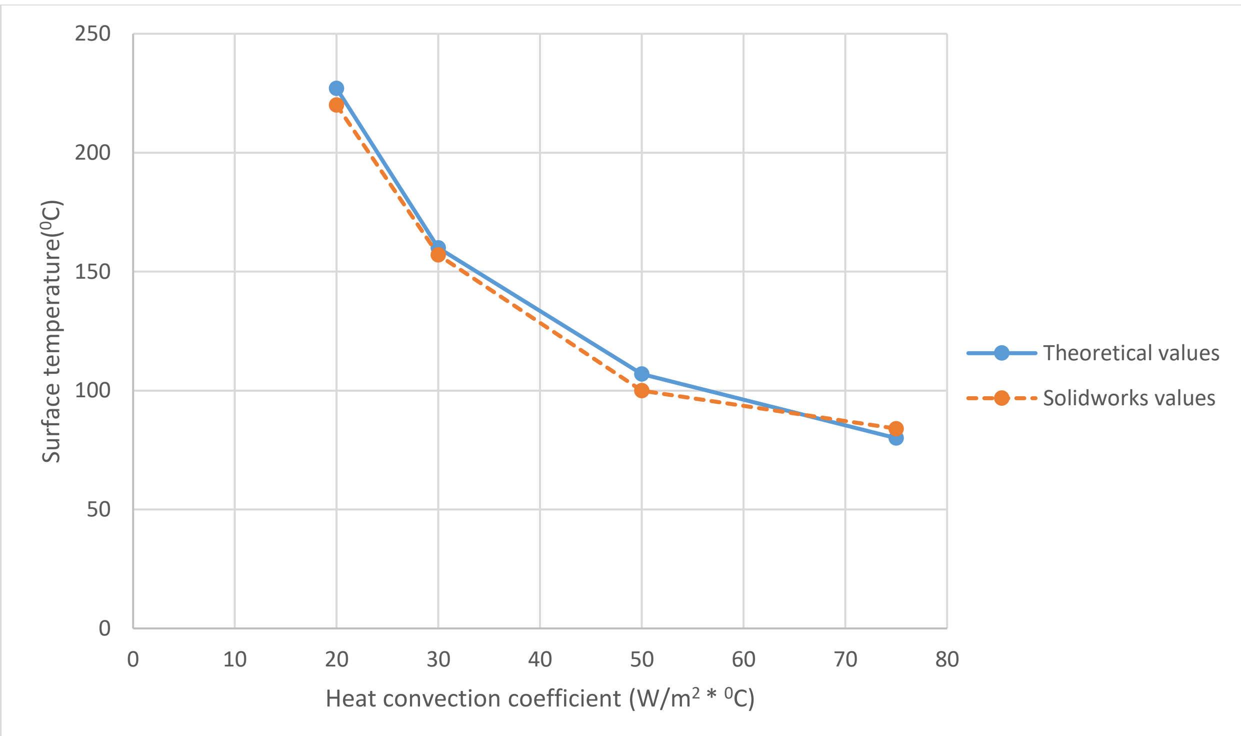

Figure 15: Results comparison of Calculated & FEA

Heat dissipation

Temperature exceeding above 82°C will damage most hydraulic cylinder’s functioning by degrading the quality of oil. This is mainly due to, operating a hydraulic cylinder above 82°C will affect most of the hydraulic fluids viscosity. Losing the viscosity of the fluid leads to degradation of cylinder’s efficiency [25].

Therefore, for reducing the temperature to 82°C or below we need to calculate the excess heat to be dissipated from the cylinder.

HP = $0.001 * A * dT$

HP is a unit for calculating the heat radiation from the surface (HP=745W)

A is the total surface area(m)^2 of the system which is in contact with fluid as well as ambient temperature

dT is the temperature difference between system's temperature and ambient temperature.

A= 0.1m^2; dT_1 = 182°C; dT_2 = 39.5°C

HP_1 = $0.001 * A * dT_1$

= 0.35

HP_2 = $0.001 * A * dT_2$

= 0.1

Therefore, heat difference which must be created using a heat exchanger = $HP_1 - HP_2$ = 0.25 HP = 186W

3.3 Fins calculation

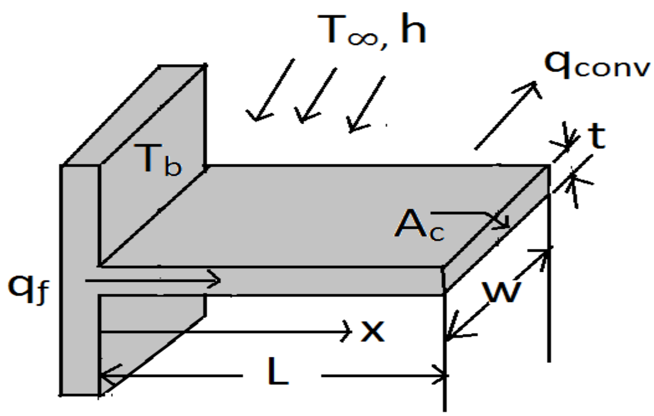

Figure 16: Parameters of fins

"A_S" is the perimeter of the selected region of the fin.

$$A_S = P_x$$

$$\frac{dA_S}{dx} = P$$

$$P = 2w + 2t$$

“A_C" is a point on fin which is considered for simplified calculation.

$$\dot{Q}_x = -KA_C \frac{dT}{dx} \quad (3.2)$$

$$\dot{Q}_{x+dX} = \dot{Q}_x + \frac{d\dot{Q}_x}{dx}\, dx$$

$$d\dot{Q}_{Conv} = hA_S\,(T_S - T_\infty) \quad (3.3)$$

According to first law of thermodynamics energy can neither be created nor be destroyed, it will be simply transformed into other form of energy. Here in our case, energy will be transferred in the form of heat convection into the body and will be released in the form of excess heat into the surroundings.

$$\dot{Q}_x = \dot{Q}_{x+dx} - (-d\dot{Q}_{Conv})$$

$$\dot{Q}_x = \dot{Q}_x + \frac{d\dot{Q}_x}{dx}\, dx + hdA_S\,(T_S - T_\infty) \quad (3.4)$$

$$\frac{d}{dx}\left(A_C\ \frac{dT}{dx}\right) - \frac{h}{k}\frac{dA_S}{dx}\,(T_S - T_\infty) = 0$$

$$\frac{d^2T}{dx^2} + \frac{1}{A_C}\frac{dA_C}{dx}\left(\frac{dT}{dx}\right) - \left(\frac{1}{A_C}\frac{h}{k}\frac{dA_S}{dx}\right)(T_S - T_\infty) = 0 \quad (3.5)$$

Therefore, Uniform fins are designed in which the area “A_C" remain constant throughout the length of fin.

So, $\frac{dA_C}{dx} = 0$

$$\frac{d^2T}{dx^2} - \left(\frac{1}{A_C}\frac{h}{k}\frac{dA_S}{dx}\right)(T_S - T_\infty) = 0$$

From the equation

$$\frac{d^2T}{dx^2} - \left(\frac{hP}{A_Ck}\ \frac{dA_S}{dx}\right)(T_S - T_\infty) = 0 \quad (3.6)$$

“θ" is the excess temperature, that is required to be removed from cylinder surface.

$$\theta\,(x) = T(x) - T_\infty \quad (3.7)$$

$$\frac{d^2\theta}{dx^2} - m^2 = 0$$

Where m^2 is equal to $\frac{hP}{A_Ck}$

General solution of the equation leading to,

$$(1 - m^2) = 0$$

$$\theta\,(x) = C_1\, e^{mx} + \; C_2\, e^{-mx} \tag{3.8}$$

Under steady state condition, Heat transferred from exposed surface of fin is equal to the heat conducted to the fin at its base.

Parameters of fins are shown in table no 4.

Table 4: Geometrical parameters of fins

Parameters	**Value**
Fin length	375 mm
Fin thickness	5mm, 10mm, 15mm, 20mm
Fin spacing	50mm
Number of fins	72
Fin width	1mm
Ambient temperature	27°C
Heat convection	5, 10, 20 (w/m^2.k)

4 Results & Discussions

For thermal analysis, a 3D FEM analysis called SOLIDWORKS simulator is used to study the rate of cooling of the hydraulic cylinder with respect to convectional cooling. Generally, there are two types of studies which can be performed using this software, namely steady state, and transient state. In steady state analysis, there will not be any time constraint whereas transient state analysis requires initial parameters like temperature and time. Thermal loads will be applied as a function of time in the case of transient thermal analysis.

4.1 Thermal study of Hydraulic cylinder

Study properties:

In the FEA analysis Heat power and convection are the loads used for conducting the thermal study and they are explained in the below table no 5. Temperature dependent thermal properties ae taken into consideration as the study requires ambient conditions. For simplifying the study all the outer exposed surfaces including the piston rod’s surface irrespective of its strokes are assumed with similar thermal conditions.

Material properties:

All the components of the hydraulic damper assembly including Cylinder, Piston rod, and the piston are assigned with a common material type of stainless steel, assuming the model as a linear elastic isotropic type. Stainless steel consists of a minimum of 18% chromium, 8% of nickel with a combination of maximum 0.08% Carbon. Some of the thermal properties of this material is shown in the table no 5.

Table 5: Parameters of Material properties

Material properties	Value
Specific heat	460 J/(kg.K)
Mass Density	7700 kg/m^3
Thermal conductivity	16.2 W/(m.K) at 100°C 21.4 W/(m.K) at 500°C
Melting Temperature	1400°C

Thermal loads:

In SolidWorks thermal analysis thermal loads or restrains are defined by temperature, convection, heat power, heat flux and heat radiation. In natural convection of heat, the rate of convection will be very low at the ambient conditions making outside surface temperature of cylinder hotter. For calculating, rate of increase in temperature the thermal loads were defined as shown in table no 6.

Table 6: Properties of Thermal load

Thermal load	**Value**
Convection coefficient	20 W/(m^2.K)
Bulk ambient temperature	298 K
Heat power	40 W

A convection coefficient of 20 W/(m^2.K) at a bulk ambient temperature of 298 K is applied on all the exposed faces of the cylinder along with the piston rod making a total entities count of 11. A total heat power of 40 W is applied on all the 3 faces of inner walls of cylinder or through the piston's stroke length.

Meshing properties:

While meshing a solid part or an assembly, the simulator will generate either a draft quality mesh or high quality mesh based on the active mesh options of the study. A draft quality meshing consists of linear tetrahedral solid elements and a high-quality meshing consists of parabolic tetrahedral solid elements. Explaining further, a linear tetrahedral element consists of 4 corner nodes connected by 6 straight edges. During the simulation, high quality meshing is adapted for better results. Advantages of using a high-quality meshing is, they signify curved boundaries more accurately compared to the other type. As the accuracy in defining the boundaries increases, the mathematical approximation also increases yielding better and accurate results of the analysis.

Table 7: Meshing Parameters used in thermal study of HC

Mesh type	Solid mesh
Mesher used	Curvature based mesh
Jacobian points	4
Mesh quality	High
Total nodes	15890
Total elements	9225

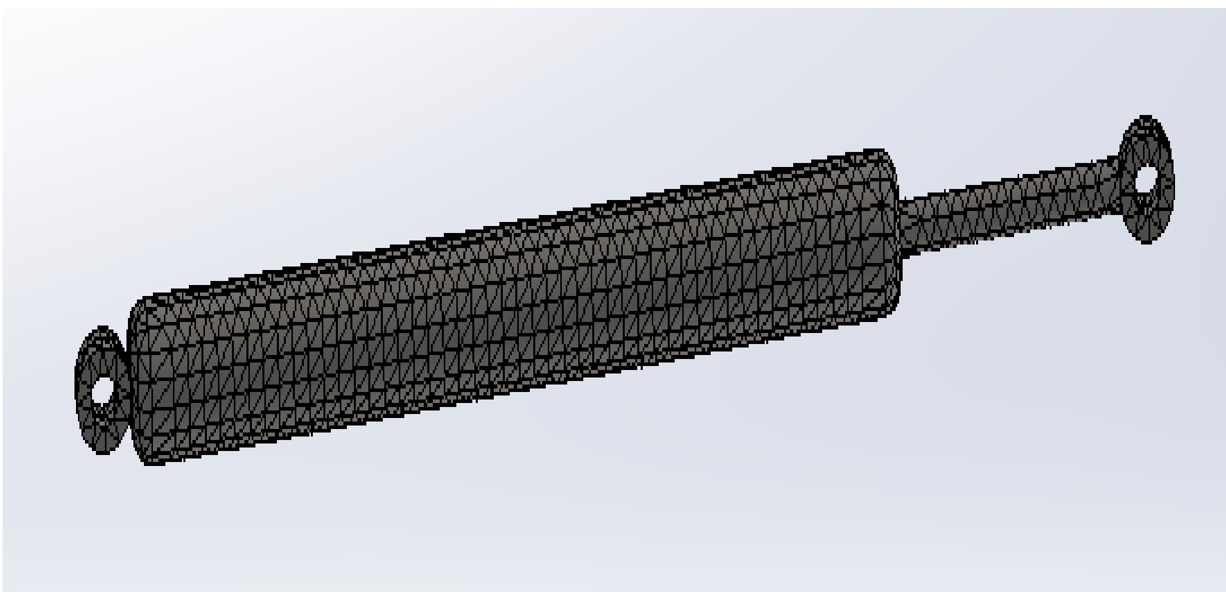

Figure 17: FE mesh of hydraulic cylinder

An overview of the mesh created by meshing is shown in the above Figure 13 and the fineness of the mesh and its uniform distribution all along the surface of the assembly can be clearly observed.

Results of thermal study of hydraulic cylinder

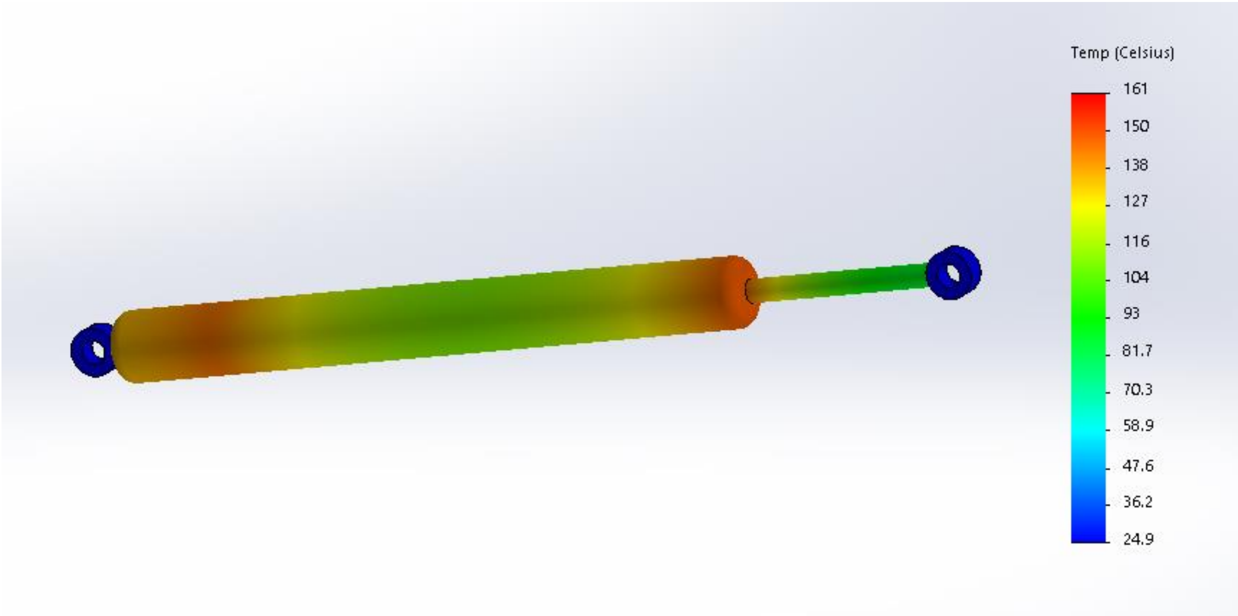

Figure 18: Hydraulic cylinder body Temperature distribution at a convection coefficient of 20 W/(m^2.K)

After generating the mesh and running the solver based on all the properties assigned, a maximum temperature of 166°C and a minimum temperature of 25°C will be observed from the results obtained. As shown in the Figure 14, the zone in red represents the maximum temperature and the blue represents the minimum temperature.

For attaining the safe working temperature of the hydraulic cylinder, it is required to perform several iterative processes to define temperature distribution on the cylinder assembly by increasing the heat convection. As the heat convection increases the maximum temperature of the solid assembly decreases and the same process of simulation is repeated until an approximate maximum temperature of around 40°C is attained by the solver. Material properties, meshing and contact properties remain same during all the iterative process.

During all the iterations, thermal loads like Heat power and bulk ambient temperatures remain constant while convection coefficient varies. All the results from the iterations are tabulated as below table number 8, including the range of heat convection applied for conducting the thermal analysis. Table is developed between the varying convection coefficient and the decreasing maximum temperature.

Table 8: Variation in temperature distribution at different h_c

Convection coefficient(W/(m^2.K))	**Maximum temperature(°C)**
20	166
30	131
40	101
50	84
100	63
150	59
200	56
250	53
300	50
350	49

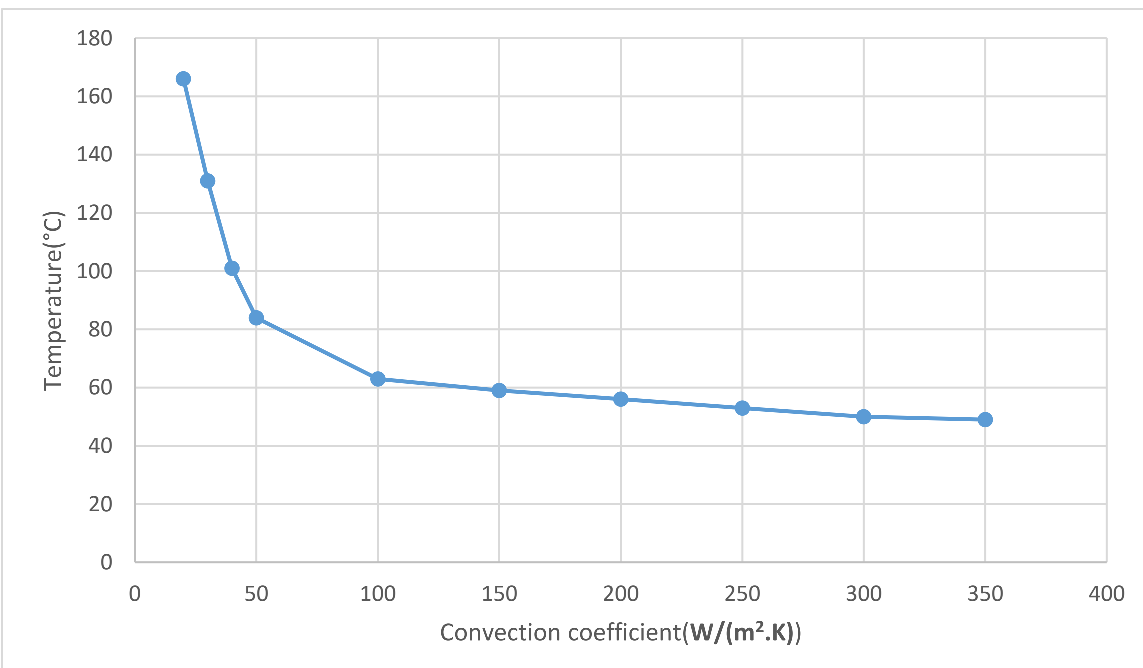

Figure 19: Dependency of temperature on convection coefficient

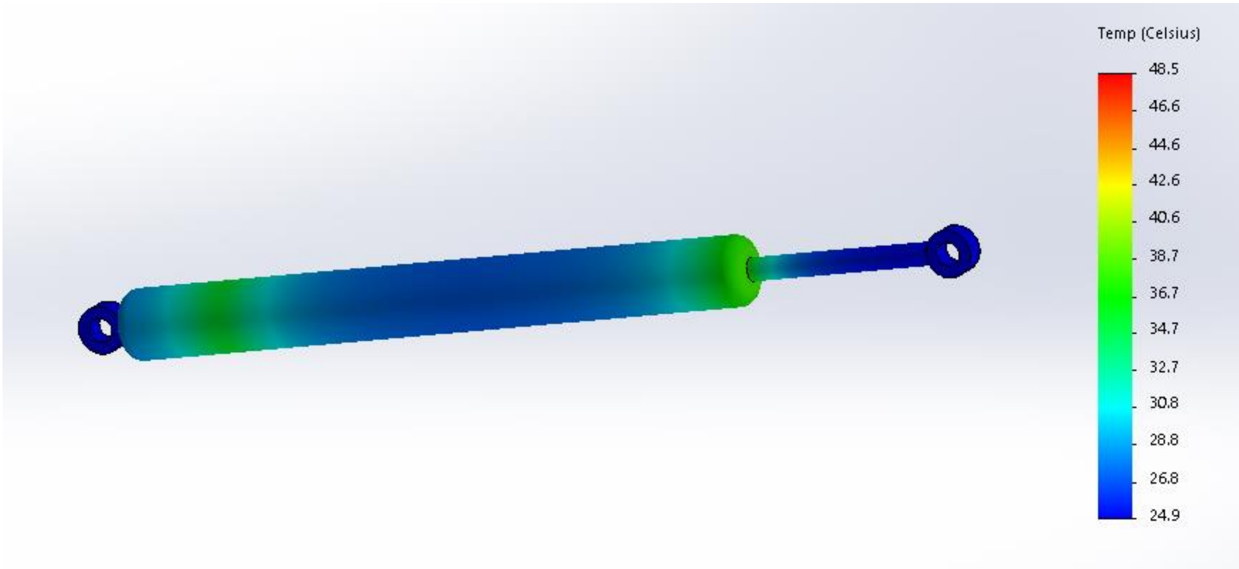

Figure 20: HC body Temperature distribution at a convection coefficient of 450 W/(m^2.K).

We can observe from the above Figure 15, that an allowable temperature of 49°C is attained by our iterations by defining the convection coefficient of 350 W/(m^2.K). By using the data from the iterations performed using FEM thermal analysis, a cooling device is to be designed for attaining the allowable maximum working temperature practically.

4.2 Thermal study of Hydraulic cylinder with fins

Based on the previous results from the thermal analysis, fins are designed for achieving the required heat convection by increasing the surface area. Both longitudinal and radial fins are designed and thermal analysis is performed and compared.

Longitudinal fins

Longitudinal fins are designed and assembled around the cylinder surface thus increasing the surface area of cylinder. A total of 72 fins with constant longitudinal length and varying heights are assembled around the cylinder surface and thermal analysis is performed using the SolidWorks simulation. Assembly of fins can be clearly observed from Figure 16.

Figure 21: Assembly of hydraulic cylinder with longitudinal fins

Material properties:

All the components of the hydraulic damper assembly including Cylinder, Piston rod, and the piston are assigned with a common material type of stainless steel, assuming the model as a linear elastic isotropic type. Material properties of the assembly excluding the fins can be referred from table number9. Material of the fin is defined as aluminum alloy. Aluminum alloy consists of aluminum, Copper, Iron, Magnesium, Manganese, Silicon, Titanium, Vanadium, and Zinc and material compositions of these elements are shown in the table no 9.

Table 9: Material composition of aluminum alloy 1060

Material	Composition range %
Aluminum	99.6% minimum
Copper	0.05% maximum
Iron	0.35% maximum
Magnesium	0.03% maximum
Manganese	0.03% maximum
Silicon	0.25% maximum
Titanium	0.03% maximum
Vanadium	0.05% maximum
Zinc	0.05% maximum

Thermal loads:

For calculating, rate of increase in temperature the thermal loads were defined as shown in table no 10. Thermal loads are assigned similar as the previous analysis.

Table 10: Thermal loads acting on hydraulic cylinder with longitudinal fins

Thermal load	Value
Convection coefficient	20 W/(m^2.K)
Bulk ambient temperature	298 K
Heat power	40 W

Meshing properties:

Similar to the previous meshing parameters, high quality mesh is used. Additionally, Mesh control is used to specify different element sizes at different regions of model as the fin's structure is complex compared to the cylinder's. Properties of the mesh are tabulated below in Table. 11.

Table 11: Meshing properties of hydraulic cylinder with longitudinal fins

Mesh type	Solid mesh
Mesher used	Curvature based mesh
Jacobian points	4
Mesh quality	High
Total nodes	373779
Total elements	227637

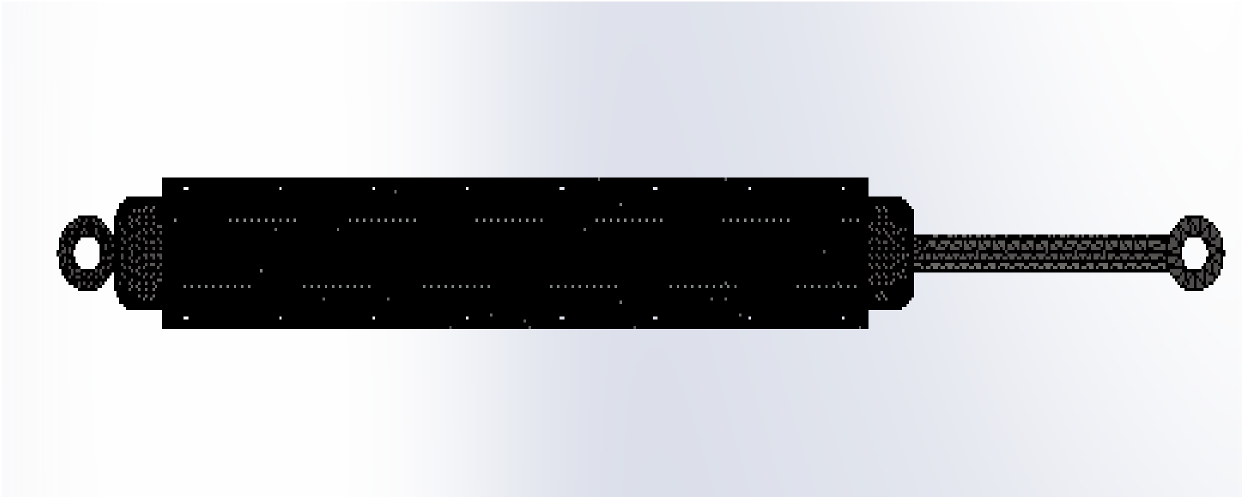

Figure 22: FE Mesh of hydraulic cylinder with longitudinal fins

Results of Thermal study of Hydraulic cylinder with longitudinal fins

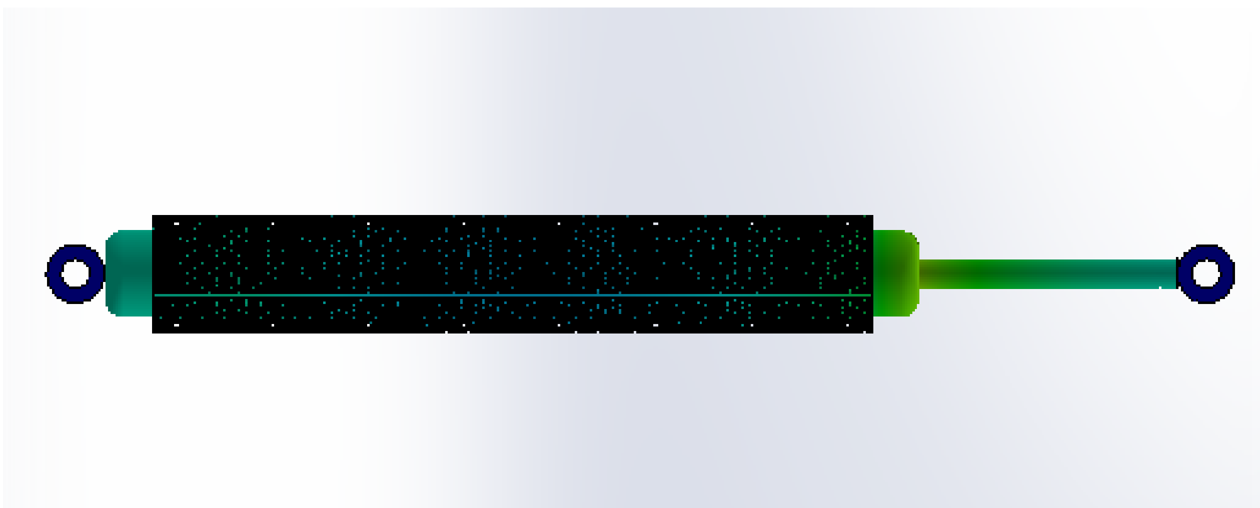

Figure 23: Temperature distribution on a cylinder assembly with longitudinal fins

After generating the mesh and running the solver based on all the properties assigned, a maximum temperature of 65°C and a minimum temperature of 25°C will be observed from the results. For attaining the safe working temperature of the hydraulic cylinder, it is required to perform several iterative processes to define temperature distribution on the cylinder assembly by increasing the height of fins. As the height of fins increases, the maximum temperature of the solid assembly decreases and the same process of simulation is repeated until an approximate maximum temperature of around 40°C is attained by the solver. Material properties, meshing and thermal properties remain same during all the iterative process.

Table 12: Range of temperatures generated on a hydraulic cylinder with longitudinal fins

Height of fins (mm)	Maximum temperature (°C)
5	65
10	59
15	42
20	37

We can observe from the above Table 12, that an allowable temperature of 40°C is attained approximately by our iterations by increasing the fin's height gradually to 15mm. By using the data from the iterations performed using FEM thermal analysis fin height from 15mm is acceptable for achieving the desired rate of cooling.

Radial fins:

Radial fins are designed and assembled linearly along the cylinder surface thus increasing the surface area of cylinder. A total of 72 fins with constant longitudinal length and varying heights are assembled around the cylinder surface and thermal analysis is performed using the Solidworks simulation. Assembly of fins can be clearly observed from figure. 19

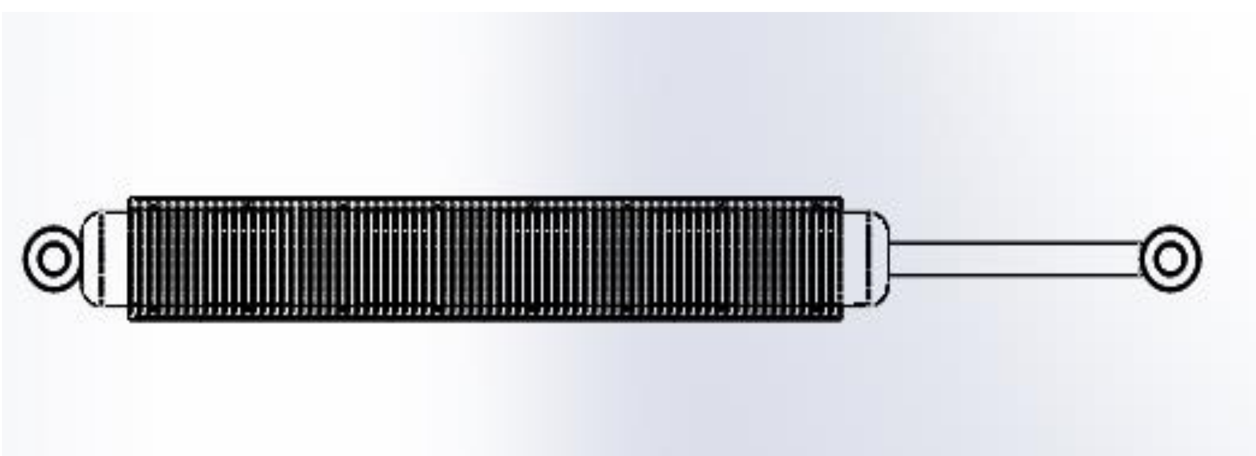

Figure 24: Assembly of hydraulic cylinder with radial fins

Material, thermal and meshing properties are defined same as the properties assigned in longitudinal fins thermal study, refer to Table 10. for material properties, Table 11 For thermal properties, Table 12 For meshing properties.

Figure 25: FE Mesh of a hydraulic cylinder with radial fins

Results of Thermal study of Hydraulic cylinder with Radial fins

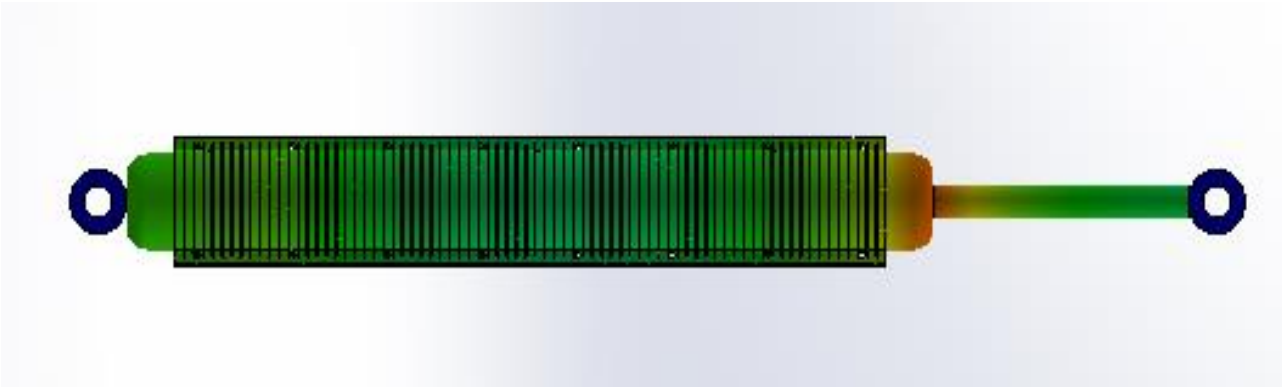

Figure 26: HC body Temperature distribution at a convection coefficient of 20 W/(m^2.K) with radial fins

After generating the mesh and running the solver based on all the properties assigned, a maximum temperature of 81°C and a minimum temperature of 25°C will be observed from the results. For attaining the safe working temperature of the hydraulic cylinder, it is required to perform several iterative processes to define temperature distribution on the cylinder assembly by increasing the height of fins. As the height of fins increases, the maximum temperature of the solid assembly decreases and the same process of simulation is repeated until an approximate maximum temperature of around 40°C is attained by the solver. Material properties, meshing and thermal properties remain same during all the iterative process.

Table 13: Range of temperatures generated on a hydraulic cylinder with radial fins

Height of fins (mm)	Maximum temperature (°C)
5	81
10	71.5
15	61
20	55

We can observe from the above Table 13, that a temperature of 55°C is attained approximately by our iterations by increasing the fin's height gradually to 20mm. By using the data from the iterations performed using FEM thermal analysis fin height from 15mm is acceptable for achieving the desired rate of cooling.

Comparison of results:

By comparing the results of thermal analysis conducted using both the longitudinal and radial fins a graph is plotted with the dependency of increase of height versus convection coefficient. Results are compared by referring the values from Tables 12 & 13.

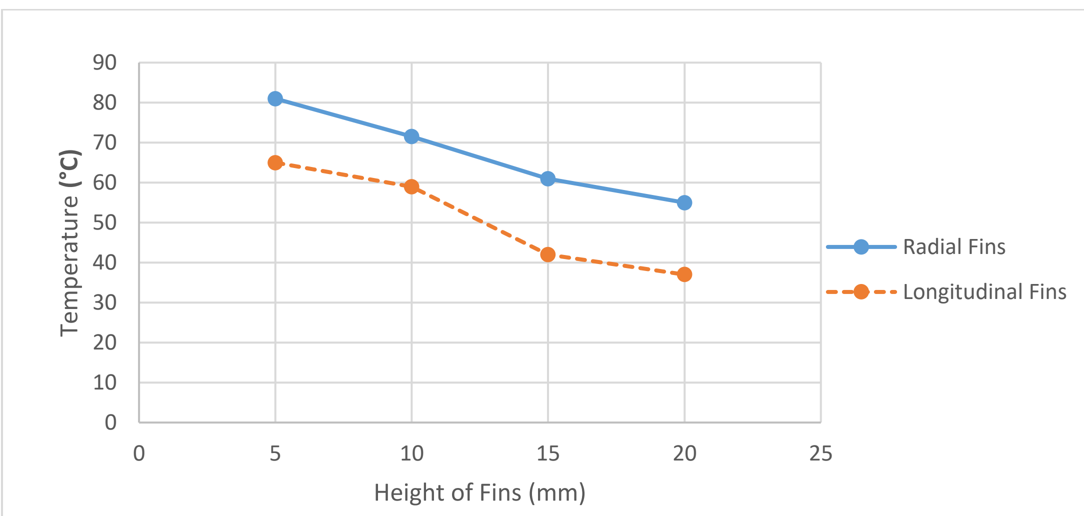

Figure 27: Comparison of Radial and Longitudinal fins efficiencies

From the comparison, variation in temperature distributions is observed in both radial and longitudinal fins models. The rate of cooling in the case of longitudinal fins are approximately ~30% more than the rate of cooling in radial fins. As discussed earlier, safe operating temperature for hydraulic cylinder at ambient conditions are 40℃.

Conclusion

To improve the performance of a hydraulic cylinder of the lever type rowing machine by improving its cooling rate the analysis of design, regimes and principles of operation of the hydraulic cylinders, heat transfer mechanisms and cooling systems was carried out; the thermal loads acting the present design cylinder of rowing exerciser and excessive heat to be dissipated were determined by computational analysis of its thermal state. For that purpose, the 3D CAD models of the present design of hydraulic cylinder used in hydraulic rowing machine was created and its thermal state analysis was performed by means of 3D CAD software Solidworks and Solidworks Simulation. Forces and thermal loads acting on the hydraulic piston were also calculated theoretically, and results of theoretical calculations were compared with results of computer simulation. It was obtained that:

- 40 W heat power corresponds the energy affecting the hydraulic cylinder during exercising and to be dissipated to keep stable temperature of the cylinder;
- A maximum of 350 W/(m^2.K) convection coefficient is required to be created which is not possible by natural convection.

Two types cooling devices (having longitudinal and circular cooling fins) were designed which are able to be mounted onto the rowing exerciser’s cylinder and this way to improve the rate of heat transfer to the environment by increasing convection. Their efficiency was evaluated by means of their thermal state analysis performed by Solidworks Simulation FEA code. Computations of different configuration (aluminum alloy fins height: 5 mm, 10 mm, 15 mm and 20 mm and convection intensity) showed that at convection coefficient 20 **W/(m^2.K) which is** most adequate to real exercising condition:

- Maximum temperature of the cylinder in case of cooling unit with 15 mm height longitudinal fins reaches 42°C when nominal 40 W heat power is applied on the internal surfaces of the hydraulic cylinder;
- Maximum temperature of the cylinder in case of cooling unit with 15 mm height circular fins reaches 61°C when nominal 40 W heat power is applied on the internal surfaces of the hydraulic cylinder;
- At the same (15 mm) height longitudinal fins are ~30% more effective than radial fins at the same cooling conditions (convection coefficient of 20 **W/(m^2.K))** thereby are more suitable for improving the cooling rates of hydraulic cylinder of rowing exerciser. In addition, their manufacturing (extrusion) is simpler than for unit containing circular fins.

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