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INSTITUTE OF AUTOMOTIVE ENGINEERING
ÚSTAV AUTOMOBILNÍHO A DOPRAVNÍHO INŽENÝRSTVÍ

DESIGN OF A PROTOTYPE DEVICE FOR ASSEMBLING COOLER INSERTS
KONSTRUKCE PROTOTYPOVÉHO ZAŘÍZENÍ PRO SKLÁDÁNÍ VLOŽEK CHLADIČŮ

MASTER'S THESIS
DIPLOMOVÁ PRÁCE

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VEDOUCÍ PRÁCE

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Assignment Master's Thesis

Institut: Institute of Automotive Engineering
Student: **Bc. Jiří Hanák**
Degree programm: Automotive and Material Handling Engineering
Branch: no specialisation
Supervisor: **Ing. Jiří Bazala**
Academic year: 2022/23

As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Master's Thesis:

Design of a prototype device for assembling cooler inserts

Brief Description:

Prototype production of heat exchangers is important in terms of both verification tests before series production and small series production. Selecting the appropriate design of the jig for stacking exchanger inserts can increase the efficiency of the process and bring the prototype production closer to the mass production.

Master's Thesis goals:

Research on possible solutions for the design of a folding device.
Selection of the most suitable folding device concept for a specific size of heat exchangers.
Device design – manual/pneumatic drive.
Control calculation of the designed device.
Creating production drawings.

Recommended bibliography:

STONE, Richard. Introduction to internal combustion engines. 3rd edition. Warrendale, Pa.: Society of Automotive Engineers, 1999. 641 s. ISBN 0768004950.

Deadline for submission Master's Thesis is given by the Schedule of the Academic year 2022/23

In Brno,

L. S.

prof. Ing. Josef Štětina, Ph.D. Director of the Institute	doc. Ing. Jiří Hlinka, Ph.D. FME dean

ABSTRACT

This master's thesis focuses on the design of a new improved assembly device of radiator cores used in prototype production. This new design aims on increasing efficiency of the assembly process and shortening the assembly time. In the research part of this master's thesis are described different types of cooling systems and individual components of the cooling system with focus on the construction of the radiators. Next there are described different types of assembly devices used in the assembly process and the original design of the assembly device with its problems characterised. Based on the research part of this thesis the assignment of the new assembly device is defined and two conceptual designs of the assembly device are introduced together with several solutions to critical construction areas. From two conceptual solutions was one solution selected and its main construction areas were verified with necessary calculations or analysis. The assembly drawing of the new assembly device was created. Finally, a new improved assembly device design is introduced and evaluated.

KEYWORDS

Radiator, assembly device, radiator cooling tube, radiator fin, assembly process

ABSTRAKT

Tato diplomová práce se zaměřuje na návrh nového a vylepšeného skládacího zařízení určeného pro skládání vložek chladičů v prototypové výrobě s důrazem na zvýšení efektivity procesu skládání a snížení výrobního času. V rešeršní části této diplomové práci jsou popsány rozdílné typy chladicích systémů včetně jednotlivých komponentů obsažených v chladících systémech s hlavním zaměřením na konstrukci chladiče. Dále jsou popsány rozdílné typy skládacích zařízení používané v procesu skládání vložek chladičů a je charakterizován původní návrh skládacího zařízení včetně jeho aktuálních problémů. Na základě rešeršní části této práce je definováno zadání nového skládacího zařízení a představeny dvě koncepční řešení s několika variantami řešení kritických konstrukčních uzlů. Ze dvou koncepčních řešení bylo vybráno jedno finální a jeho kritické konstrukční uzly byly prověřeny nutnými výpočty nebo případnou analýzou. Následně byly vyhotovena výkresová dokumentace nového skládacího zařízení. Nakonec je představen nový vylepšený návrh skládacího zařízení, který je poté zhodnocen.

KLÍČOVÁ SLOVA

Chladič, skládací přípravek, chladičová trubka, chladičový vlnovec, skládací proces

BIBLIOGRAPHICAL REFERENCE

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AFFIDAVIT

I declare that this master's thesis is my original work, I created it by myself under the supervision of Ing. Jiří Bazala and using information sources listed in the references at the end of this thesis.

In Brno 26th of May 2023 ……..……..…………………………………………..

Bc. Jiří Hanák

ACKNOWLEDGEMENT

I would like to thank my supervisor Ing. Jiří Bazala for the helpfulness and valuable notices he gave me throughout my work on this thesis. Also, I would like to thank the management of the R&D department of Hanon Systems Autopal Services s.r.o. for providing me important feedback during the creation of the practical part of this thesis.

SUMMARY

INTRODUCTION

Every piston combustion engine is equipped with some type of cooling system. The cooling systems used in modern passenger cars are constantly being upgraded and adjusted to fit actual demands of the vehicle manufacturer. This progress goes along with improvements of the radiator production. Before each new radiator is authorized for mass production, firstly the prototype must be made and then it needs to be properly inspected and tested to meet the assigned demands. Variety of different dimensions, shapes and constructions of the radiator means that it is quite complicated and time consuming to make a functioning radiator prototype. To make the prototype radiator production easier, the assembly devices are used. They are usually simple or one-purpose devices which significantly help the operator with the radiator prototype production to meet targeted requirements. Not only do they save the production time but also ensure dimension stability if more testing prototypes must be made. The design of the assembly device is something that needs to be checked since its improvements may lead to large savings in the production time and increase the production efficiency.

Theoretical part of this thesis is made in a research form, and it focuses on the cooling systems in general and on the single components of the most used cooling system which is the forced indirect cooling system. Next it summarizes the modern radiator construction and gives a short description of assembly device types which are used for radiator core production. At the end of the theoretical part of this thesis is described the design of manually operated assembly device used in prototype production of radiator cores and problems that come along with it.

The goal of the practical part of this thesis is to create a new improved assembly device design based on the defined assignment. Based on the research of this thesis and on the assignment two conceptual designs are created together with the solutions of critical areas in the new design. One conceptual design is selected, and critical areas of its construction are verified with necessary calculations. Lastly the new design of the assembly device is introduced, and the assembly drawing is created. In the conclusion of this thesis is a summary of the benefits of this improved new design and suggestions for additional improvements.

The practical part of this master's thesis was created on the basis of the requirements of the company Hanon Systems Autopal Services s.r.o. in Hluk, which deals with thermal and energy management solutions. [1]

1 AUTOMOTIVE COOLING CIRCUIT

One consequence of the operation of a combustion engine is heat. This redundant heat is produced by burning fuel in the combustion chamber and then it's transferred through conduction, convection, and radiation into almost every engine component either directly or indirectly and in some cases both approaches are used. [2] [3] [4] [5] Temperature of all parts of piston combustion engines needs to be in a certain temperature range during its operation. Maintaining reasonable temperature of all important components of combustion engine such as piston, cylinder wall, cylinder head, bearings, parts of timing mechanism etc. ensures the long lifetime period of these parts and their proper function during this lifetime period. [3] [4] Exceeding of the maximum permissible temperature of these vital engine parts and components may lead to engine power loss, lower efficiency and finally lead to destruction. [3] Warped and burned engine valves, burned oil which lost its lubricating qualities, pistons and all bearings seized is just a brief summary of consequences of engine overheating. [5]

For achieving proper temperature of all above mentioned parts and construction groups of combustion engines in general a cooling system is used. The cooling system takes heat from the engine parts and components and transfers it into the surrounding environment. [2] Its function is to keep the combustion engine's operational temperature at the required value. It is important not to exceed the maximum permissible temperature of combustion engine parts as well as to avoid low operation temperatures of combustion engine. These low temperatures can cause great damage to the piston group and reduce thermal efficiency. [3] [5] Another very important consequence of low operating temperature is greater production of pollutants in exhaust gasses which are emitted to the environment. [5]

Approximately 30 to 35 % of energy present as heat and produced by burning fuel in the combustion chamber is necessary to remove from the combustion engine to maintain its optimal operational temperature and this energy cannot be used for propulsion of the vehicle. [3] [4] [5] This value is slightly different for petrol and diesel engines due to the engine's operating cycle. Petrol engines in general produce mildly more heat than diesel engines. [3] Proper cooling system lowers the tendency for detonation combustion. [4]

Well-designed cooling system must also comply with a few conditions. Which are to maintain optimal operational temperature as it was already mentioned and making sure that engine oil temperature does not exceed maximum permissible value after which it loses its lubricating properties. [4] A well-designed cooling system is expected to have high cooling performance, general low weight, high efficiency, and it should be able to prevent thermal stress of engine components by even cooling. [4]

Cooling systems can be divided into direct cooling systems (air cooled systems), indirect cooling systems (liquid cooled systems) or their combination. [4]

1.1 DIRECT COOLING SYSTEM (AIR COOLED SYSTEMS)

Direct cooling system is based on a principle of removing heat from the combustion engine by exposing its warmest parts to the surrounding environment. [3] Air from the surrounding environment is forced, sucked, or thrusted during movement of the vehicle and as a result it absorbs heat and takes it away. [4] This type of cooling system has very simple construction, ensures quicker warming of the combustion engine to operational temperature and has very low service requirements. [3] [4] Direct cooling system is also light, in comparison with indirect cooling systems there is no risk of cooling liquid leakages and may be used in conditions with very low ambient temperature. [5] On the other hand, it has higher noise level than indirect cooling systems as well as higher operational temperature in combustion engines which requires use of high-quality materials for combustion engine components and this type of cooling systems has lower efficiency. [3] [4] [5] Also, it is important to take in account the operational temperature fluctuation because of the instantly changing ambient conditions like speed of the vehicle and ambient air temperature. [2] Most characteristic feature of this type of cooling system are cooling ribs designed on the cylinder head and cylinder barrel which supply additional conductive and radiating surface to the combustion engine. [4] [5] These ribs make more heat radiation areas, which helps to dissipate the heat efficiently and quickly. Usually, each individual engine cylinder and engine head has it’s set of cooling ribs designed during manufacturing. [4] Efficiency of the direct cooling system depends on the amount of the ambient airflow, fin surface area and thermal conductivity of the fin material. Some types of combustion engines with direct cooling systems may use oil liquid cooling to maintain optimal operating temperature. [5] Direct cooling systems can be typically found in cooperation with piston combustion engines used in motorcycles, trucks, aviation, tractors and other small machinery. [3]

Direct cooling systems can be divided into thrust direct cooling systems and forced direct cooling systems. [3]

1.1.1 THRUST DIRECT COOLING SYSTEMS

Thrust direct cooling systems use the force of the ambient air flow around the engine cooling ribs. Airflow is increased with higher speed of the moving vehicle. This cooling system is very often used for cooling the motorcycle engines. It is because of the general motorcycle construction, which allows the combustion engine to be mounted without covering. [3] [4]

1.1.2 FORCED DIRECT COOLING SYSTEMS

Forced direct cooling systems use the force of the ambient airflow around the engine cooling ribs as well as thrust direct cooling systems, but the force of the airflow is generated by a cooling fan externally mounted on the engine and in some cases directed with types of coverings. The amount of the airflow created by the fan is not dependent on the vehicle speed. [3] Cooling fans can be radial or axial construction and they are powered from crankshaft via gear mechanism or pulleys and belts. One of the most typical forced direct cooling system representatives in the Czech Republic is the air-cooled engine used in Tatra trucks. This representative uses a unique construction of cooling fan, which is powered via hydrodynamic clutch and triggered when engine oil reaches a certain temperature [4]. There are other possibilities how cooling fan can be controlled like choking airflow at the inlet or outlet of the cooling fan, controlling cooling fan rev, changing the vane pitch etc. There is also several types of cooling fan connecting clutches like hydrodynamic as it was already mentioned, electromagnetic, hydraulic, viscous and powder clutches. [3] Disadvantage of this cooling system is its lower cooling efficiency compared to forced indirect cooling system mainly because it is complicated to design the forced direct cooling system to maintain the optimal operating temperature of the combustion engine during all operation modes. On the contrary, the forced indirect cooling systems can be designed with performance reserve. Also, the cooling fan can take up to 10 % of the total brake power of the combustion engine. All these described reasons caused that the forced indirect cooling systems are no longer used for passenger vehicles. [6] [7]

1.2 INDIRECT COOLING SYSTEM (LIQUID COOLED SYSTEM)

Indirect cooling systems are closed systems and use liquid as a medium to collect the unwanted heat from engine components and transfer it into the heat exchanger. Heat exchanger then passes the heat into the surrounding environment and returns cold cooling liquid back into the system. Indirect cooling systems are commonly connected with the heating of the cabin or air condition. [3] [4] Cooling liquid used in indirect cooling systems usually consist of a mixture of distilled water and additives such as ethylene-glycol, propylene-glycol, and etc. [8] This mixture used in the indirect cooling system ensures trouble-free operation of the cooling system against surrounding conditions in cold temperatures in winter and also hot ambient temperatures in summer. [3]

Automotive cooling systems need to be designed so it can well maintain optimum operating temperature in all ranges of ambient conditions. This includes all ranges of ambient temperatures together with all ranges of vehicle speeds. [4] The great advantages of indirect cooling systems are overall lower temperature of all combustion engine components which results in less thermal stress and therefore cheaper material for these components can be used. Other advantages are better cylinder weight filling with fresh fuel mixture, higher volumetric engine power, usage of hot cooling liquid for heating the passenger area and its noise insulating characteristics. [3]

Basically, all modern engines in the automotive industry are equipped with indirect cooling systems. [3]

Indirect cooling systems can be divided into four categories. Thermosiphon otherwise called gravitational indirect cooling systems, indirect cooling systems with forced circulation, combination of gravitational and forced circulation indirect cooling systems and lastly evaporative indirect cooling systems. [3]

1.2.1 THERMOSIPHON INDIRECT COOLING SYSTEM

Thermosiphon indirect cooling systems work on a principle of different densities of hot and cold cooling liquid. The warm coolant has lower density than the colder coolant and it results in rising the warm coolant in the cooling system and cold coolant replacing it. [3] [4] Different densities are causing the coolant to circulate from cold parts of the heat exchanger on the lowest part of the engine through the jacket of cylinder walls to cylinder head which is the highest and hottest part of the engine and therefore no water pump is needed. [5] The coolant then returns to the heat exchanger which makes the cooling circuit complete. Radiators in this type of cooling system need to have a significant approach temperature of almost 30 °C. The biggest issue of the thermosiphon indirect cooling system is its low circulating speed. Due to its low value the cooling channels would need to have a significant cross section thus creating a big mass of cooling liquid in the system. This only leads to more issues such as slower warming of the engine and complicated engine bay construction requirements. As a result, since the late 1940s thermosiphon indirect cooling systems were replaced by forced indirect cooling systems. [3]

In the picture below is an illustration of the thermosiphon indirect cooling system with several of its components described.

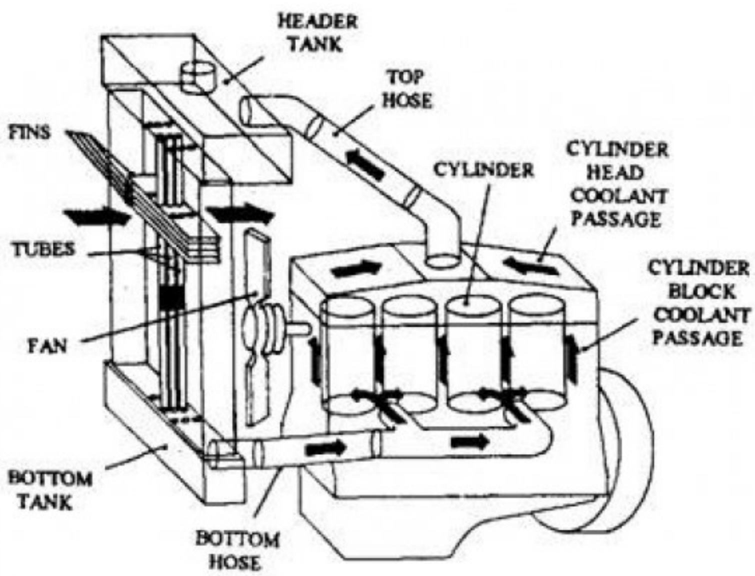

Figure 1 Schematic illustration of coolant flow in the thermosiphon indirect cooling system [39]

1.2.2 FORCED INDIRECT COOLING SYSTEM

Forced indirect cooling systems are the most used and most efficient cooling systems for the automotive industry. They are more complex and have more complicated construction than air cooled combustion engines which results in more service requirements. [4] [5] The cooling power in forced indirect cooling systems is achieved with combination of ambient airflow and heat dissipation in the radiator. [5] The powering element is a circulating pump which is forcing the coolant to run through the series of cooling channels inside the cylinder walls, cylinder head, around valve seats and through hoses in the cooling system. These channels which are inside cylinder walls and cylinder head are called jackets. [5] The circulating pump can be powered for example mechanically from the crankshaft via pulley and belt. [4] Radiator in this cooling system need to have approach temperature between 6 to 12 °C. Forced indirect cooling systems includes except a circulating pump also cooling fan, radiator and a thermostat which is dividing the cooling system into the short (bypass back to engine) and long circuit (including radiator). [3] [5]

After starting the combustion engine, the thermostat is closed which is forcing the cooling liquid to circulate in a small cooling circuit and as a result making the engine quicker reach the operating temperature. After the combustion engine reaches the operating temperature, the thermostat starts to open, and the cooling liquid can flow in a big cooling circuit. Thanks to proper control of the cooling fan and well-functioning thermostat perfect engine temperature is guaranteed at all combustion engine operating modes. [3] Efficiency of an indirect cooling system can be increased by improving several important cooling system characteristics like increasing cooling liquid circulating speed in the cooling system, increasing maximal cooling liquid operating temperature or increasing heat exchanger radiation area. [4]

This statement can be verified by following formula which is the Fourier's law [9]:

$$q = -k\,A\,\frac{\Delta T}{\Delta x} \tag{1}$$

Where the q is the rate of heat flow through an area A and thickness Δx. The ΔT across the thickness Δx is the temperature change. The conductivity of the material is parameter k.

On the other hand, it is also important not to forget how these improvements can have an impact on combustion engine fuel consumption, overall engine weight increase or for example can make complicated construction requirements. [4]

The forced indirect cooling systems also have disadvantages. The cold cooling liquid flows first through cold parts of the engine cylinders and after it is heated up then flows to the hotter parts of the engine cylinders and cylinder head. [3] There is also a risk of overheating in case of water pump failure. [5]

The cold cooling liquid with temperature of 40 - 60 °C flows from the radiator to the water jackets inside the cylinders where the cooling liquid reaches the temperature of 80 – 90 °C. Then the cooling liquid flows to the thermostat which directs the cooling liquid to flow either in short cooling circuit back into the water jackets or in the long circuit back to the radiator. The cooling fan is mounted behind the radiator to provide additional airflow if it is needed. [10]

The picture below represents the forced indirect cooling system with description of the main parts.

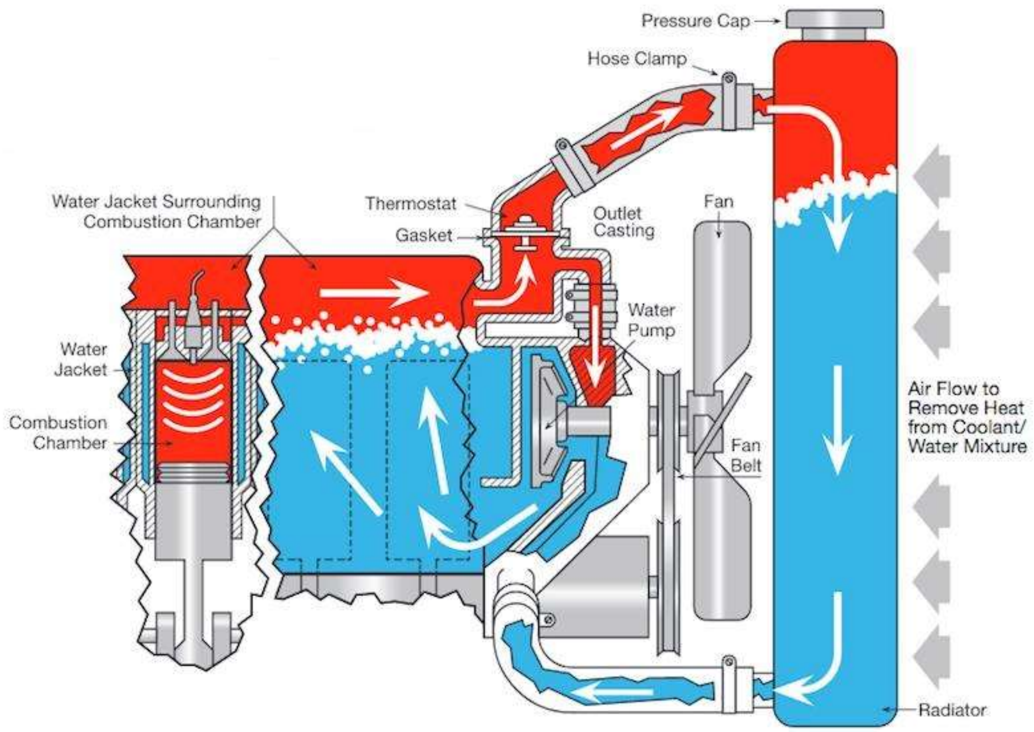

Figure 2 Schematic illustration of the cooling liquid flow in the forced indirect cooling systems [40]

1.2.3 COMBINED INDIRECT COOLING SYSTEM

Combined indirect cooling system uses principles of both above mentioned types of indirect cooling systems. It contains a circulating pump which has the purpose of supplying freshly cooled cooling liquid directly into upper parts of cooling channels of engine cylinders or cylinder head. Lower parts of cylinders or entire cylinders are cooled down by using gravitational flow of cooling liquid. [3]

On the figure below are represented the parts of the combined indirect cooling system. Cooling liquid flow (3) coming from the radiator outlet is forced by water pump (8) into the water cooling jackets (1) and then rises into the cylinder head (7) where is directed by the thermostat (9) into the hose (6) and to the radiator inlet. The cooling fan (5) is creating the additional airflow.

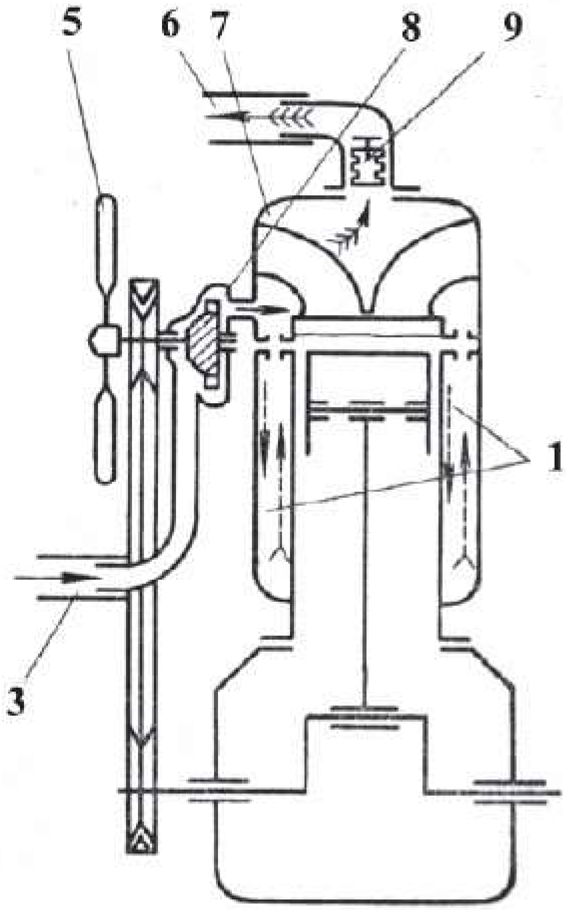

Figure 3 Schematic illustration of the combined indirect cooling system [3]

1.2.4 EVAPORATIVE INDIRECT COOLING SYSTEM

Last type of indirect cooling system works on a principle of evaporation. Cooling liquid absorbs the heat from the combustion engine and then changes from liquid phase to vapour phase. This results in transferring the heat into the surrounding environment. This type of indirect cooling system is considered as the oldest type of engine cooling system in general and was described as loss-cooling. [11]

In the picture below is outlined the evaporative indirect cooling system.

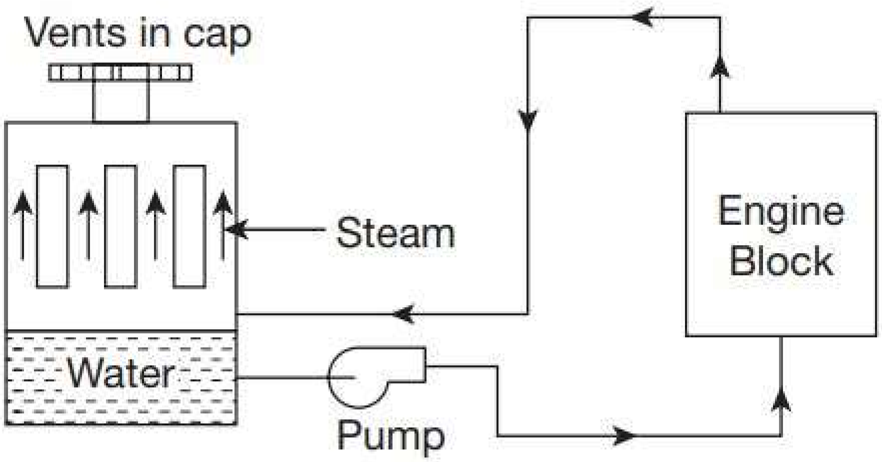

Figure 4 Schematic illustration of the evaporative indirect cooling system [41]

2 COMPONENTS OF CONVENTIONAL COOLING SYSTEM

Most used cooling system in the automotive industry is the forced indirect cooling system and it is composed of several important components which are represented below, and which will be shortly described further.

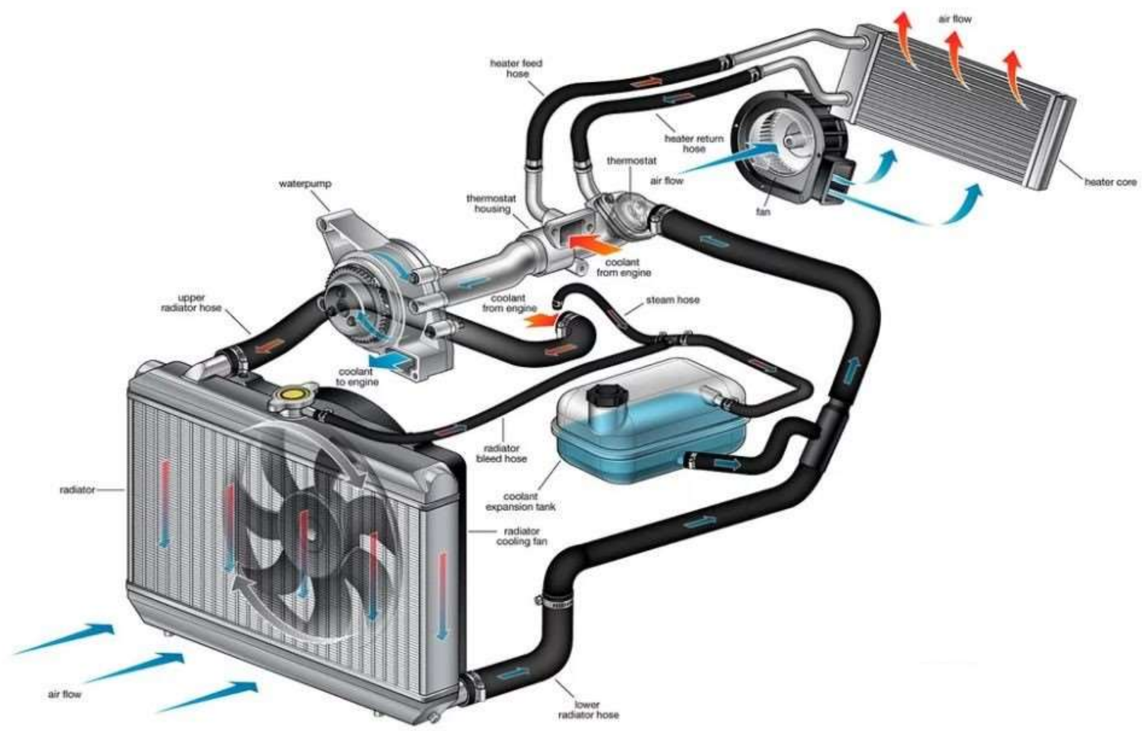

Figure 5 Components of the conventional cooling system [42]

2.1 WATER PUMP

As it was already mentioned, a water pump is a key component to an indirect cooling system. It ensures required cooling liquid flow inside the cooling channels of engine cylinders and cylinder head in the cooling system. [3] [5] Water pump has to guarantee the most uniform heat distribution in cooled parts of the combustion engine and also prevent formation of steam in the hottest parts of the cooling system such as parts of cylinder walls in contact with piston rings, engine head around exhaust ports, and etc. [4] Thanks to a higher cooling liquid velocity inside the cooling system a bigger cooling effect can be achieved. This mechanism helps the combustion engines to reach a better performance. [4]

In automotive cooling systems typically a one stage rotational centrifugal (radial) water pump is used. Water pumps consist of stator filled with cooling liquid and rotor - impeller. Rotor has radial vanes which take the cooling liquid from the stator inlet and push it to the stator outlet. [4] Water pump stator can be made from cast iron or aluminium alloys. Rotor material is cast iron, aluminium alloys or nowadays plastic. [3] The rotating speed of the water pump is usually higher than the rotating speed of the crankshaft even though they are mechanically connected regularly via a pulley and belt. [4] The water pump can be also powered through timing belt or common serpentine belt, which is connecting the alternator or power steering pump or air condition compressor. [12] The outlet pressure of the water pump should be designed so cooling liquid can completely circulate through cooling system between seven to twelve times per minute and outlet pressure should be set at a value which prevents from cavitation in cold parts of engine cylinders. Water pump inlet speed should be between 2,5 $m.s^{-1}$ to 3 $m.s^{-1}$ and circulating speed of cooling liquid in cooling channels should not exceed 1 $m.s^{-1}$, these parameters meet the requirements of outlet pressure of 0,05 MPa to 0,15 MPa. The water pump can be designed to be powered with an electric motor. This design with electronic regulation helps to precisely control and regulate the cooling liquid circulating speed and as a result it can adapt to actual ambient conditions and operating mode of the combustion engine which can increase fuel economy, decrease friction loss and exhaust gas emissions. [1] [4] The electric water pump is also appropriate to use in cooling systems for combustion engines with start/stop technology. For electric vehicles, fuel cell or hybrid vehicles it is necessary to use this type of water pump. [1]

2.2 COOLING FAN

To ensure required cooling power of the cooling system it is necessary to deliver an adequate amount of ambient airflow to the radiator. That is achieved with a cooling fan mounted either on the engine or radiator assembly. Cooling fan creates additional airflow directed to the radiator and it is triggered in situations when it is necessary. The cooling fan consists of a rotor with blades mounted on the centre shaft secured in the stator. Triggering of the cooling fan depends on operating conditions like ambient temperature and preventing overheating due to small travelling speed and thus low airflow cooling the radiator and other components. [3] [4]

Cooling fan is powered either directly from the crankshaft, mechanically via pulley and a belt or with a built-in electric motor. [4] Cooling fan can also be mechanically connected with water pump and designed to be powered by pulley and a belt from the crankshaft. [4] [5] Another possibility is to connect mechanically the cooling fan with numerous types of clutches. [4]

Nowadays it is modern to power the cooling fan with a built-in brushless DC electric motor. This construction is reflecting the operating mode and ambient conditions of the vehicle and can adjust the cooling power of the cooling system. [1] Also the vanes of the cooling fan can have special wave-like form design which has significant impact on airflow. [13] This can positively affect the fuel consumption, lower the noise level and improve the durability of the cooling fan. [1]

Electronic control of the cooling fan during movement of the vehicle allows to precisely change rotating speed of the cooling fan and this can positively affect the fuel consumption. In simple terms the cooling fan is powered on only in slow vehicle speeds and during higher vehicle speeds the ambient air flow is enough for proper cooling power of the cooling system. As a result, the power of the electric motor of the cooling fan for the automotive industry is surprisingly low, somewhere between 60 W to 100 W. [4] These values are valid for cooling fans used with combustion engines for passenger vehicles. Modern electric vehicles use cooling fans with higher power typically around 600 W. [14] For massive combustion engines typically used in bigger machinery the power of the electric motor of the cooling fan can reach up to approximately 6 % of maximal power. [3]

Modern forced indirect cooling systems may use two to three cooling fans to ensure the proper cooling power. [4] [5] For passenger cars it is common to use the cooling fan in a single or a double arrangement. [15]

2.3 THERMOSTAT

Thermostat is the controlling and regulating component in forced indirect cooling systems. It maintains the optimal operating temperature of the combustion engine around 90 to 95 °C and it is located at the engine cooling outlet close to the engine cylinder head. [3] [4] After start of the combustion engine the thermostat is closed, and it starts to open once the temperature of the cooling liquid reaches optimal value and remains fully open in high engine loads. It also helps the combustion engine to quickly reach the operating temperature. The temperature of the cooling liquid can rise to a critical value when big steam bubbles are created in the cooling system. [4]

Operating principle can be described on a simple bellows thermostat. It contains brass flexible metal bellows which is partially filled with liquid with lower boiling point than the cooling liquid used in the cooling system. Liquid used in this bellows thermostat is typically alcohol, ether, or acetone. Inside the bellows there is no air present, only the liquid. Vapour pressure of the liquid is equal to the pressure inside the bellows, and it is temperature dependent. At the atmospheric pressure the liquid is at its boiling point and as the temperature of the cooling liquid goes higher the less pressure is present in the bellows. At the stem of the bellows is connected a popped-type or butterfly valve which controls the flow of the cooling liquid. [5] [16]

There are several types of thermostat construction like liquid (bellows) thermostat or wax thermostat. The thermostat can be also electronically preheated. [3] The wax thermostat has almost similar operating principle to the bellows thermostat except instead of the liquid there is used a wax which changes its volume when it melts. The construction of the wax thermostat is slightly different with the main element being a metal cylinder filled with a certain type of wax. In this metal cylinder there is inserted a thrust pin surrounded by a rubber sleeve with seal to prevent the wax from escaping. Also, in this type of thermostat there is a poppet-type of valve used together with spring which is responsible to hold the valve in shut position. As soon as the cooling liquid warms up the wax thermostat the wax begins to melt and expand. This leads to pushing the thrust pin out and the valve begins to open. [16]

Modern vehicles use an electronic cooling liquid temperature regulator which is similar to conventional thermostat. Biggest difference of these two components is that the electronic cooling liquid temperature regulator also includes logical core which is controlled by the electronic control unit. This means that cooling liquid temperature can be regulated with much more precision. [4]

2.4 OVERPRESSURE CAP

Another important component in forced indirect cooling systems is an overpressure cap mounted on the top of the reservoir tank. Reservoir tank is used to help expand the volume of the cooling liquid in the cooling system and used for filling the cooling liquid. With increasing pressure in the cooling system, the boiling point of the cooling liquid is also increased. This leads to greater cooling performance of the cooling system and approach temperature on the radiator. Advantage of this improvement is that a smaller radiator can be used, or the cooling system can be designed with a significant cooling power reserve. [4]

Overpressure cap works on an easy principle of relieving pressure when critical value is reached or sucking fresh ambient air if the combustion engine is stopped. It has a simple construction of spring-loaded valve and if the engine is stopped and the pressure starts to decrease, and vacuum is starting to create then there is a risk of deformation of the radiator because of the influence of the ambient pressure. [3] [4] [5]

Maximal permissible operating pressure of the forced indirect cooling system is between 0,13 to 0,20 MPa for passenger vehicles and between 0,05 to 0,11 MPa for utility vehicles. [4]

2.5 COOLING LIQUID

The cooling liquid used in forced indirect cooling systems is composed of antifreeze compounds (for example propylene glycol or ethylene glycol) and distilled water mixed in specific ratios. Mixing ratio sets the freezing point and the most typical ratio is 50:50. [4] [5] [15] Maximal permissible mixing ratio is 75:25. Pure antifreeze used in the cooling system can cause boil over. [5] Since the cooling liquid contains anticorrosive inhibitors, antifoaming agents, and the antifreeze compound it can be used all year and should be replaced in accordance with the cooling system manufacturer. The cooling liquid is subject to natural ageing. [15] Used additives also help to prevent creating sediments which can negatively affect the cooling system performance and can help with increasing the cooling liquid boiling point. [4] The optimal cooling liquid used in forced indirect cooling systems should have optimal heat transmission properties, low evaporation losses and high-thermal capacity. Other optimal cooling properties which can be mentioned are well corrosion, anti-cavitation and erosion protection, good temperature stability, long service life and should have good compatibility with materials used in the cooling system. [15] Maximum permissible operating temperature of the cooling liquid is 100 to 120 °C for passenger vehicles. Maximum permissible operating temperature of the cooling liquid used in utility vehicles is slightly lower around 90 to 95 °C. These values differ according to the specific cooling system, instructions from the cooling system manufacturer etc. [4] Regular interval for the cooling liquid used in the automotive industry is two years. [17] Volume of cooling liquid in forced indirect cooling system is somewhere between four to six times of cylinder capacity. [4]

2.5.1 THE COOLANT VALVES

To efficiently flow control strategies of the cooling liquid in the cooling system the electronic coolant valves are used. The coolant valve is essentially a DC-motor driven ball valve which helps to direct the cooling liquid through various cooling loops (circuits). [18] The coolant valve has multiport construction which lowers the number of actuators used in the cooling system. They are electronically controlled which results in less energy consumption in comparison to solenoid valves and can be used in modern vehicles equipped with start/stop technology or for electric, hybrid and fuel cells vehicles. [1]

3 RADIATOR

Radiator or heat exchanger is the crucial component of every cooling system. As it was already mentioned, heat exchanger helps to dissipate heat into ambient air and thus helps to lower the combustion engine operating temperature to optimal level. [3] Complete radiators consist of radiator core, inlet and outlet header and sealing gasket (O-ring) between. The radiator core itself consists of side panels, faces, tubes, and fins. These components will be furthermore described. In some applications it is common that the radiator includes a transmission oil radiator or engine oil radiator or exhaust gas cooler. [4] [15]

The picture below represents the construction of a horizontal radiator. On the sides of the radiator are inlet and outlet headers (1) mounted into header plates (6). Between the headers and the header plates is placed a sealing gasket (3). The radiator core consists of the cooling tubes and radiator fins (4) pressed into the header plates (6) and reinforced on the sides with the side panels (5). On the bottom side of the picture is illustrated the engine oil radiator, consisting of cooling tubes and radiator fins (8) supported on the sides with side panels (5). These components of the engine oil radiator are pressed into the engine oil header plate and closed with headers (7). The heat exchanger cooling liquid / oil (2) is mounted inside the inlet header.

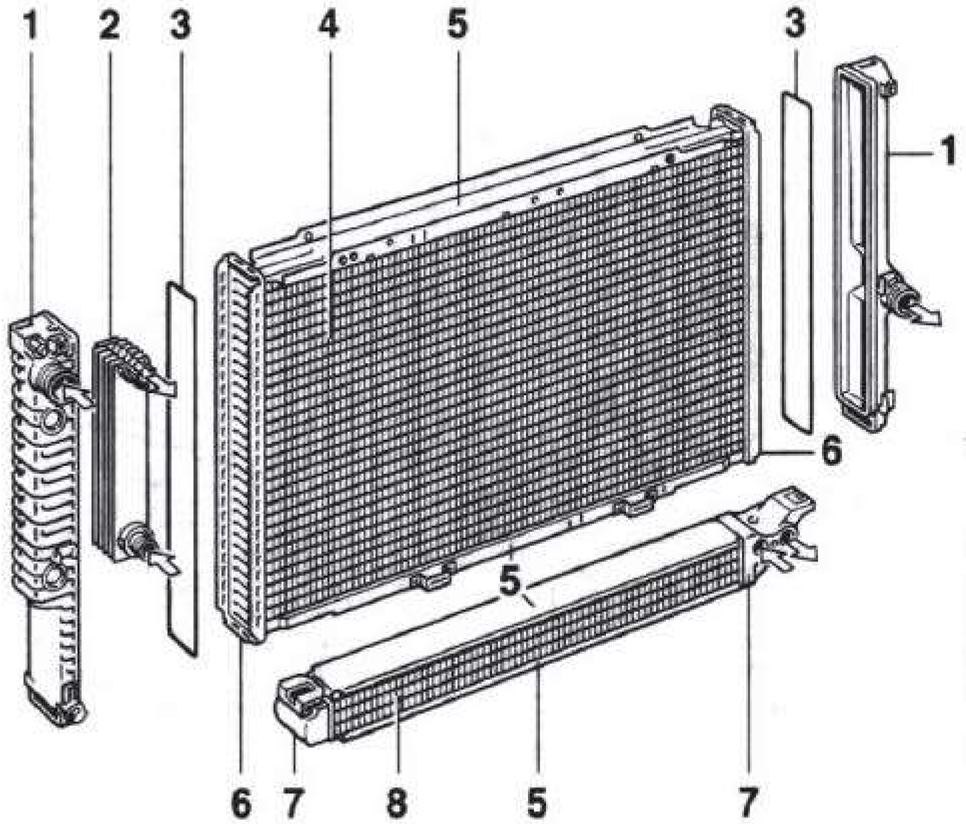

Figure 6 Horizontal radiator construction [3]

Functional principle is that cooling liquid enters the radiator from a hose connected to the inlet header. Cooling liquid is then forced to flow through cooling tubes to outlet header and during this process relives its heat to ambient air. The radiator can have vertical or horizontal cooling liquid flow construction and can be single row or double, triple row construction. [4] [19]

The vertical construction of the radiator consists of a radiator core with cooling tubes oriented vertically. Inlet header is mounted on the top side of the radiator, and it is connected to the reservoir tank which has volume of approximately 25 – 30 % of complete cooling system volume. [3] In case of isobaric cooling systems there is an overflow pipe connected to the inlet headers and this pipe supports the system if there is an unwanted overpressure or possible vacuum. Inlet header can be also equipped with an overpressure cap and no reservoir tank is used. Outlet header is mounted on the bottom of the radiator and is connected to the inlet header through the radiator core. Vertical radiator construction is commonly used in cooling systems for heavy machinery. [4]

The horizontal construction of the radiator is most popular in modern automotive cooling systems. Inlet header is mounted on one side of the radiator and cooling liquid is forced to flow to the other side of the radiator where the outlet header is mounted. This described arrangement of non-divided inlet and outlet headers is typical for horizontal radiators used in non-performance vehicles and most passenger cars and it is called the single pass radiator. Each end of the cooling tubes is connected to different headers. For increasing the cooling performance of the radiator, the inlet and outlet headers can be internally split into inlet and outlet sections by a divider which creates a longer path for the cooling liquid to flow and thus increasing cooling power of the radiator. This type of the radiator is called double pass radiator. [4] [19]

Radiator is mounted on the vehicle frame via rubber bushings which reduce vibrations and shocks transmitted to radiator construction. Inlet and outlet of the radiator is connected via rubber hoses with textile insert or if there is necessary to connect radiator with other parts on longer distances a plastic or metal tube is used. [4]

Maximal permissible pressure inside the radiator is 200 bars (g) and maximal permissible temperature is 200 °C. [20]

3.1 Compact cooling module

Nowadays the radiator is mounted together as a single unit with many components of the cooling system. [1] [15] The cooling module can be composed of components like a radiator, climate control heat exchanger, intercooler for pressure charger, shroud, transmission oil cooler and cooling fan. Since the 1980s there has been high demand for these compact cooling modules used in passenger cars cooling systems for its undeniable benefits. Firstly, its compact design is suitable for smaller mounting space in the engine bay and there is less development, testing and assembly cost for the cooling system manufacturer. This compact module is regularly mounted to the transverse or longitudinal members of the passenger vehicle and one of the components (typically radiator) is used as the main supporting element. Other parts of the compact cooling module are bolted, clipped, snapped, or clamped to this main element. [15]

The picture below represents the parts of the compact cooling module. Behind the front grill is the radiator joined together with a fan shroud and two cooling fans. Behind the cooling fans is mounted another heat exchanger.

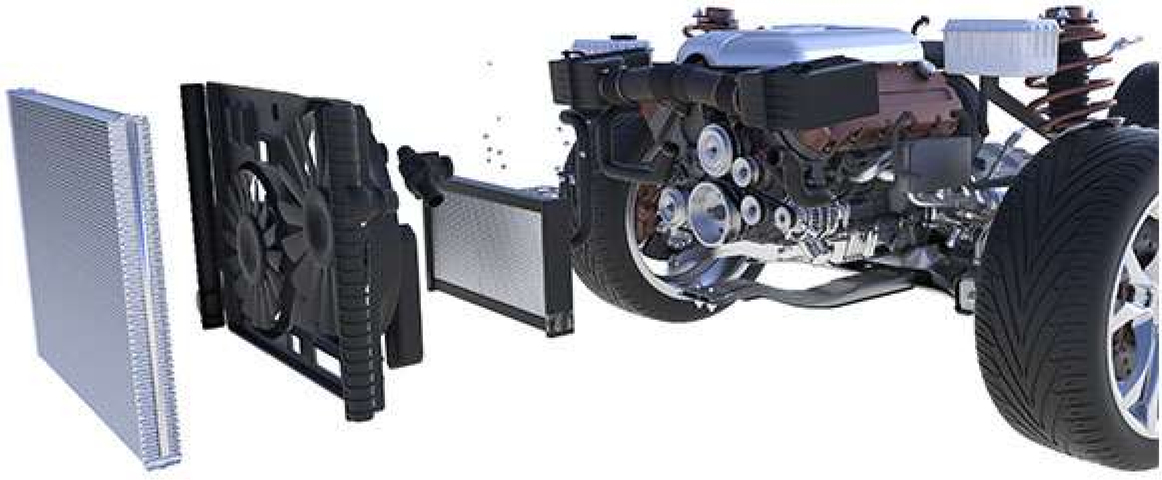

Figure 7 Schematic illustration of compact cooling module [43]

3.2 RADIATOR CORE CONSTRUCTION

Radiator core is composed of cooling tubes and fins which are mounted into two header plates and reinforced on sides with two side panels. Cooling tubes and fins are properly oriented so the biggest heat transfer surface area can be created. Radiator core can be either mounted from single components or brazed together. Material used for manufacturing of the radiator core is aluminium alloy or pure aluminium. Modern automotive cooling systems use exclusively pure aluminium for radiator core manufacturing. [4] All parts of the radiator core like cooling tubes, fins, header plates and side panels are covered with rolled braze filler material and coating called flux. This very thin coating with flux has white colour and it is used as an agent to promote the brazing process. The flux is also used specially to remove the brazed material from oxides and to support the flow of the braze filler. Unfortunately, the flux is quite toxic and during the brazing the flux starts to create fumes released by decomposition of chloride and fluoride. These fumes are very toxic and dangerous to living organisms, so the flux is in remission. [21] [14] After the complete process of assembly of the radiator core it is placed into continuous furnace with protective atmosphere, where in the presence of the heat created in the furnace the braze filler begins to melt and joins all components of the radiator core into one with the support of the flux. This is the procedure, where the radiator receives its mechanical properties like strength and durability. After the final inspection of the radiator core, it can be mounted together with the inlet and outlet headers into the radiator assembly and marked as finished product. [4]

Brazed radiator cores are used in high performance cooling systems or in cooling systems with lack of mounting space, so the radiator must be compact. If there is a requirement for a cheaper type of radiator, then mechanically assembled (without brazing) radiators are used. [4]

In the picture below is a detailed view of the single components of the double row radiator core. The cooling tubes together with the radiator fins are pressed into the header plate.

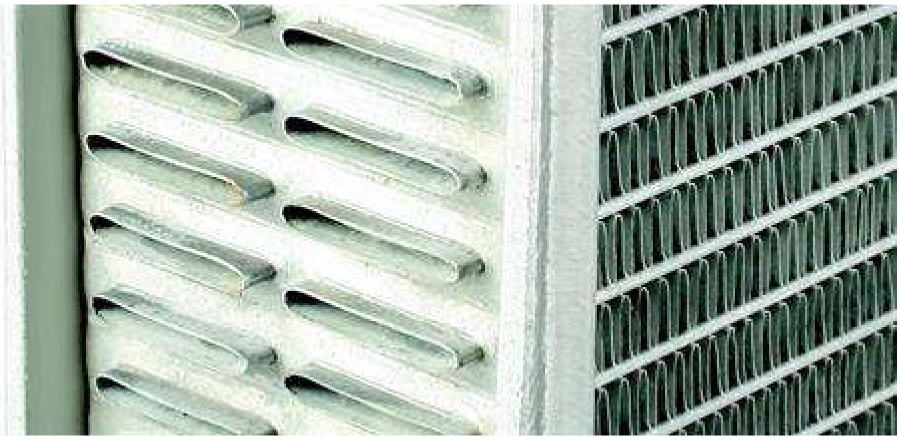

Figure 8 Detail view on the radiator core construction [19]

3.2.1 RADIATOR COOLING TUBES

Radiator cooling tubes used in automotive cooling systems can have several cross sections like circular (tubular), rectangular – flat, cellular, or oval. [4] [5]

3.2.2 RADIATOR FINS

Radiator fins are used to increase the heat transfer surface area and transfer the thermal energy. [19] They are made from aluminium, coated with braze filler and flux. The radiator fins have several different construction shapes. It is possible to divide them as plain fins, perforated fins, serrated fins, herringbone and louver fins which are most used in automotive cooling systems and passenger cars. [22] Louver fins are created from aluminium tape which is bent into desired shape and into the side of the fin there are small slots created which can have many shapes and angles which help to adjust the complete radiator to a certain application. The louver fins also increase the turbulent air flow which lead to higher heat transfer. [23] [24]

3.3 INLET AND OUTLET HEADERS

Inlet and outlet headers are in cooling systems connected to the radiator core. [4] To guarantee the tightness of the complete radiator assembly a gasket (O-ring) is mounted between the inlet and outlet headers and the radiator core. [4] [5] Inlet and outlet headers and usually secured in their permanent position by indentation created on the sides of radiator core header plates. This process of securing the inlet and outlet headers in their location is called “wavy crimp” and it is performed either manually in single-purpose machines for example in prototype production of the radiators or automatically in series production of the radiators. The sealing gasket must be pressed approximately 30 % of its thickness before mounting the radiator cores. This value is experimentally tested to be best on a long-term basis and ensures a long lifetime of trouble-free sealing characteristics. [4] [14]

The inlet and outlet headers in modern cooling systems are made of injected plastic (polyamide) reinforced with fiberglass. [4] [5] They are manufactured with all necessary connections and mounting points. Another option for headers material which was used historically is brass, copper and zinc alloy or aluminium. [4]

3.4 RADIATOR MAINTENANCE

Average lifetime of the automotive radiator used in passenger cars is approximately 250 000 km or 15 years. These values are determined by strength calculations. Concrete requirements for radiator lifetime period are stated by the automotive car manufacturer as a customer to a manufacturer of radiator assembly. Design of the radiator assembly should consider ambient conditions during vehicle operation and should be able to maintain the same cooling power during all types of weather and ambient conditions. This means that the radiator itself should be able to clean itself during normal operation of the vehicle with ambient airflow and no additional cleaning procedure is necessary. [14]

4 PROTOTYPE PRODUCTION

Prototype production is a very important step in evaluating the final product and its authorization for series production. Before the product, concretely radiators, are authorised for series production there are numerous conditions which need to be fulfilled. There are two phases of radiator design and production. First phase is design verification and the second is process verification. [14]

4.1 DESIGN VERIFICATION

Design verification includes procedure from initial assignment from the customer to the radiator assembly manufacturer to prototype manufacturing. After the correct manufacturing process, the radiator is visually inspected to confirm that all steps of the manufacturing process were done correctly. Visual inspection includes inspection of proper fin soldering and position, checking if the fins are not burned from the furnace and overall check. Also dimension inspection is crucial for the next step of inspection which is pressure decay testing. If all mentioned inspections are successfully passed the radiator goes to experimental testing where all of performance, strength and endurance parameters need to be verified. [14]

4.2 PROCESS VERIFICATION

Process verification is the next phase of radiator manufacturing. After the successful design verification, the radiator can now be passed on for series production. In series production there is a very complicated procedure of setting up the special production line for a single type of radiator. Process verification represents basically the overall check of the radiator series production. Inspected are also series production methods of the individual parts suppliers of the radiator core. Same as the design verification the process verification includes experimental testing where all of performance, strength and endurance parameters need to be verified. Since the series production is complicated theme on its own it will not be furthermore described in this thesis. [14]

5 ASSEMBLY DEVICE

The assembly device is a tool or a device that is used to help guide or fix certain components in an assembly during the assembly process. Manual assembly device helps the operator with the assembly process by saving the assembly time and keeps maintaining accuracy for all manufactured assemblies. This leads to higher productivity and makes the life of the operator easier and more comfortable. [25]

There are several aspects which should be mentioned like for example working posture, the assembly device design, and the radiator core assembly strategy. [25]

The assembly device should help the operator with few operations during the assembly process which are securely positioning the cooling tubes as well as the fins of the radiator core, pressing the composition including the side panels to a given dimension and pressing the header plates on the cooling tubes. The reason for the operation of pressing the composition to a given dimension is that the radiator cooling tubes next to the radiator fins act as a spring and have tendency to expand the radiator core to barrel-like shape.

For completing the assembly process of the radiator core a special hand tool is used. For example, better sealing of the cooling tubes I achieved with breaking tool which is hammered into the pressed cooling tubes. For better transport, manipulation, and safety the brazing frame is used, or the finished radiator cores are tied with metal string. Another tool which was not yet mentioned is a small wooden or plastic board with a handle used for pressing on the radiator core in the assembly process from the top side. It helps to arrange the misplaced radiator fins to desired position.

5.1 WORKING POSTURE AND ERGONOMICS

One of aspects of operators' productivity is its working posture and ergonomics of the workstation area. The key is to ensure a safe working environment for the operator and enhance productivity. To increase the productivity of the assembly process, the following parameters of the workstation should be examined for potential improvement. Like workstation layout, lighting of the workstation, height of the workstation table or chair or working posture in general. The quality of the components and the equipment as well as the skill of the operator is assumed to be at the same level and not changing in the assembly process. [25] [26]

For this concrete thesis the workstation layout and lighting are not critical parameters since the main improvements must be made in the assembly device design. The height of the working station should be considered since it might greatly affect the operator's productivity. Another aspect for consideration is the working posture. The work of the operator is divided into precision work, light work, and heavy work. For each of these works a different height of the workstation table should be applied. The assembly process of the radiator core in prototype production is considered as light work and therefore the appropriate height of the workstation table should be for man operator somewhere between 900 to 950 mm. The working position of the operator can be sitting or standing, and the height of the workstation table should remain the same for both positions. The height of the operator also plays an important role in the design but for simplifying the assembly device design a standard man height will be taken in account. [25]

5.2 TYPES OF ASSEMBLY DEVICE USED IN PROTOTYPE PRODUCTION

The assembly of the radiator core in prototype production can be made with manual or automated device (assembly device). It is important to distinguish them from each other because for each type of assembly device different regulations are set and must be abided. Each manufacturer must abide by these safety regulations and both types of the assembly devices must be equipped with proper precautions to abide by these rules.

5.2.1 THE MANUAL ASSEMBLY DEVICE

In essence the manual assembly device has simple construction, and the operator is responsible for all the operations with the assembly process and with use of the assembly device. A certain number of manual skills is expected from the operator to make sure the assembly process is smoothly performed and without any wasters. Since the assembly process is completely dependent on the operator some risk of human error is present.

The use of the manual assembly device for the assembly process of the radiator core means that the operator is responsible for fixing some components in the assembly device, inserting the remaining components into the assembly device and must perform completion of the radiator core. Another step is to pass the finished radiator core into the brazing frame used in the next step of the manufacturing process which is the brazing of the radiator core in a continuous furnace.

The actual manual assembly device which is model for further design improvement will be described further in the practical part of this thesis. The assembly device typically used in prototype production is manually operated. It is placed on a regular workbench and the operator works in a standing position. The components of the radiator core are set in boxes on the sides of the workbench and the operator takes them manually. On the workbench there is enough room for the operator to place additional tools or components close to the assembly device. Because of the sensitivity of the flux coating to grease or sweat contamination on the radiator core parts, the operator must wear safety gloves.

5.2.2 ORIGINAL ASSEMBLY DEVICE CONSTRUCTION

The construction of the assembly device allows the operator only to press the composition of cooling tubes, fins, and side panels together to a given dimension. This concrete assembly device design consists of the main aluminium plate with ten slots in two rows. On the one end of the second row of slots there is a firm stopper mounted on the back side of the main plate. It is not adjustable, and the location of this stopper is the same for all types and sizes of the radiator cores. In the first row of slots there is a movable stopper mounted from the bottom. The movable stopper is controlled by a nut on a ball screw. All the ball screws move independently on each other. Both ends of the ball screw are inserted into the support bearings with housing. These housings are mounted on the back side of the main plate, same as the firm stopper. The accessible end of the ball screw has a machined hexagon end to be turned over by a ratchet with a socket or spanner to a required position. The assembly device does not contain any measuring device or visual notification of the position of the movable stoppers. To ensure the precise pressing dimension a simple wooden or a plastic board is cut to size and placed on the main aluminium plate before the beginning of the assembly process. The board acts as an easy stop for the movable stopper and prevents the operator from deforming the radiator core composition during the pressing process. One hand tool for the assembly process is used to break the ends of the cooling tubes after they are pressed into the header plates. The tool has grip and on the other side of the grip the breaking pins are machined. The breaking process is also done manually with an aluminium hammer or rubber mallet. During the breaking operation the pins are inserted into the pressed cooling tubes and hammered so the end of the cooling tubes is properly expanded in the header plate, and this provides proper seal after the brazing.

The picture below represents the original assembly device with the stop board mounted in the device.

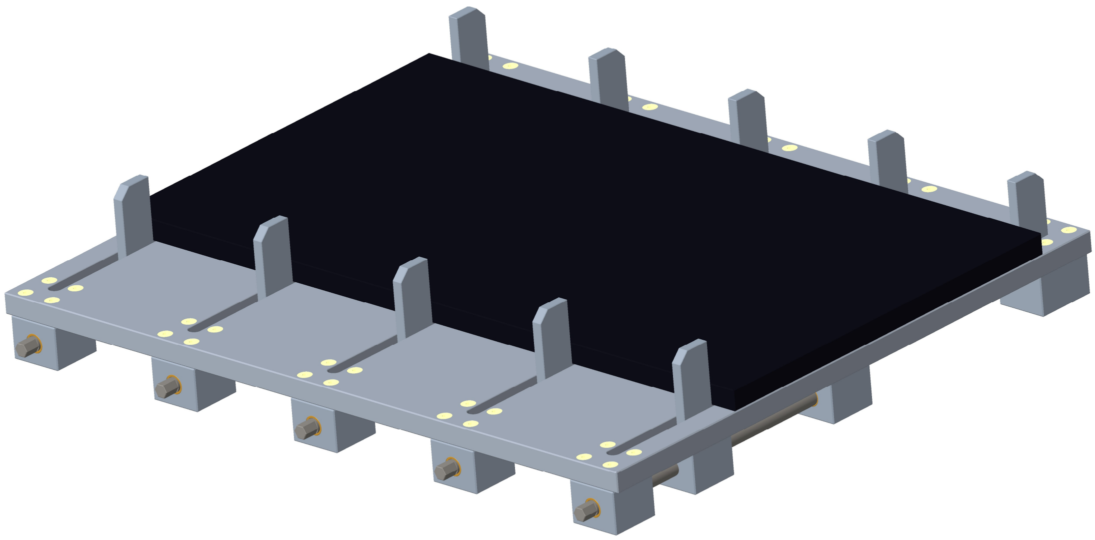

Figure 9 The original assembly device with stop board placed on the main plate

5.2.3 Assembly process

Since the assembly device does not provide additional support for this pressing process the operator firstly places a wooden stop block on the side of the assembly and secures it in place with one or more clamps. This is the beginning of the assembly process. The operator then hammers or presses all cooling tubes one at a time into one header plate of the radiator core. The header plate is firmly supported by the stop block. Then he continues with pressing the cooling tubes into the other header plate which he is holding with one and gradually pushes all the cooling tubes into demanded locations in the header plate of the radiator core. This procedure requires a great set of manual skills since the pressing process is quite delicate and must be done precisely. This precise process also contributes to the sturdiness of the cooling tubes. If the operator is not paying enough attention easily a waster can be made. Next on the assembly process is pressing of the radiator core composition. For this procedure the wooden stop block can be removed from the work bench since it will not be no longer needed. As it was already mentioned the plastic or wooden board ensures pressing to correct dimension without unwanted deformation to the radiator core. Before the pressing of the radiator core composition a small wooden board with weight of approximately 8 kg is placed on the top of the radiator core to prevent the radiator core deformation in vertical direction. This basically ends the assembly process of the radiator core. Now it is important to make sure that the dimension to which the radiator core is pressed stays until it is brazed in the furnace. For this purpose, the brazing frame is used. The brazing frame is essentially two metal bars connected with metal crossbars. The brazing frame is connected to the radiator core through two support beams placed next to the side panels. The brazing frame has notches for the required dimension of the radiator core with support beams. Once the brazing frame is placed on the finished radiator core the pressure in the assembly device is released and the required dimension of the radiator core is held with the brazing frame. The frame allows the operators and factory workers easy manipulation with the radiator core without worries of contaminating the radiator core parts by human touch or unwanted damage to the radiator core during manipulation. Positioning the brazing frame on the radiator core ends the assembly process of the radiator core.

The picture below represents the exploded view of the assembly process of the radiator core with the original assembly device and the brazing frame. The radiator core is simplified by showing only one cooling tube and radiator fin. The actual radiator composition comprises of number cooling tubes and radiator fins and the side panels are supported by the beams of the brazing frame. Lastly the header plates are in pressing position.

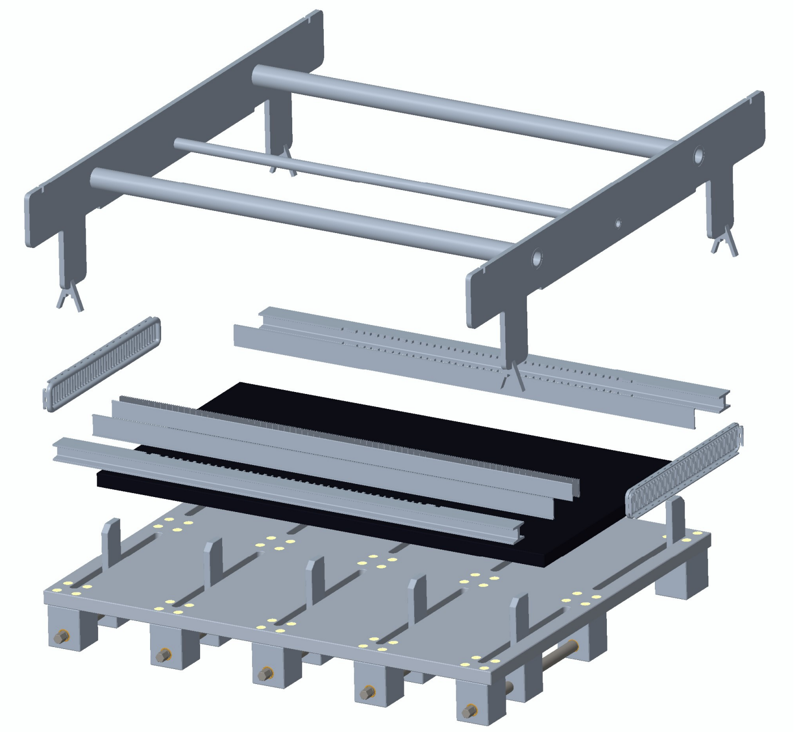

Figure 10 Schematic illustration of the assembly process

5.2.4 THE AUTOMATED ASSEMBLY DEVICE

The automated assembly device is only partially dependent on the operator. The use of the automated assembly does not require the same amount of manual skills as the manual assembly device, but strict safety precautions must be abided. The operator must be instructed how to safely operate the automated assembly device since it is composed of actuators like electric or pneumatic drives which can hurt or possibly kill the operator. Because of this danger the automated assembly device must be equipped with safety devices like optical barriers.

The optical barrier monitors the hazardous area of the automated assembly device in operation to prevent possible injuries. And in the case of the potentially dangerous situation the optical barrier shuts down the automated assembly device. [27] [28]

In the operation of the partially automated assembly device the operator is responsible for inserting the components of the radiator core in precise steps and must control the automated assembly device. The construction of the automated assembly device is composed from very sturdy linear guideways on which there are mounted parts carrying tools for each operation of the radiator core assembly process. The parts of the automated assembly device are driven through the electric motor or pneumatic cylinder. The pneumatic drive is the most common for these types of single purpose assembly devices since it offers the required amount of force to successfully perform each operation during the assembly process and it does not require much maintenance. On the market there are many manufacturers of these automated assembly devices, and they offer a variety of additional accessories to make the assembly process completely automated. Fully automated assembly process is the object of the mass production and not the prototype production of radiator cores. [27] [28]

The basis of the automated assembly devices consists of a base frame and a working table. The working table consists of a set of blocks which act as a stop from where the components are inserted and where all the radiator core assembly process takes place. On the base frame there are attached linear guideways which can be designed as linear ball bearing blocks on the guideway or as a linear rail with linear bearings which is essentially a precise shaft with sliding ball bearing blocks. On these guideways are attached arms which provide the space for tools used for different operations during the assembly process such as positioning the cooling tubes, positioning of the fins, fixing the side panels, compressing the parts, and pressing the header plates on the cooling tubes. Movement of each rail is typically provided either via electric motor like servo motor or stepper motor, or pneumatic cylinders. The design with pneumatic cylinders provides less maintenance requirements, less moving components but on the other hand there is the necessity of the supply of the compressed air. The tools are designed either for specific radiator cores or as a multipurpose for different types and dimensions of radiator cores. The actuators like electric motors or pneumatic cylinders are controlled by PLC and software specifically designed for this application. The software allows you to adjust the important parameters of the assembly process like the desired dimensions of the radiator core, speed of each operation, corrections etc. The assembly device is equipped with the safety mechanism described above in this thesis. The control of the automated assembly device is managed by a control panel with usually two main confirm buttons which must be pressed simultaneously to ensure that operators hands are out of the working area. [27] [28]

5.3 RADIATOR CORE ASSEMBLY STRATEGY

The radiator core assembly strategy may influence the assembly time. Which component will be inserted first and which one comes next may play an important role and affect the efficiency but also the complexity of the new assembly device. In the old design of the assembly device one header plate was pressed with all the cooling tubes, next the other header plate was pressed and lastly the fins were inserted. After that the pressing of the radiator core composition took place and to finish the assembly the brazing frame was placed.

The new design of the assembly device should allow the easiest operation of the assembly device for the operator and the assembly strategy should reflect that. Each of the components of the radiator core should be simply inserted into the assembly device and the precise operations of the assembly should be done by the assembly device and not the operator. The automated assembly device works on that principle and could be a good inspiration for the new assembly device design.

6 PROBLEM ANALYSIS AND MASTER'S THESIS GOALS

6.1 PROBLEM ANALYSIS

The assembly device used in prototype production of radiator cores is not a product that can be found and bought on the market. It is a special device designed for the assembly process of the radiator core. Specifically, the original construction of the assembly device is designed only for the pressing operation of the radiator core composition and its design allows it to be used only for a small range of radiator core dimensions. The pressing operation is achieved through the movement of 5 adjustable stoppers which are connected to a ball screw. Unfortunately, each of the stoppers is powered through its own ball screw leaving the operator to turn 5 different ball screws to achieve the desired pressing operation. Also, to make sure the pressing operation ends after reaching the correct dimension of the radiator core a wooden or plastic stop board is placed on the main working area of the assembly device. This stop board is cut from large laminate or plastic boards to the exact size of the radiator core. Even though the process of cutting the stop board is easy and simple the manufacturer of the radiators usually is not equipped with saws suitable to cut these materials and the stop boards must be supplied externally which only increases the cost of the radiator assembly process. The original design of the assembly device has 5 non-adjustable stoppers in the x-axis, which means that a certain assembly device can be used only for a certain length of the radiator core. This leads to multiple assembly devices in manufacturing are used for different radiator core dimensions. Another problem is that the construction of the original assembly device allows only 1 assembly operation leaving the rest of the assembly operations on the operator. This results in long assembly times of the radiator core, significant requirements for the operator workmanship and great risk of creating a waster.

On the market there are several companies who focus on manufacturing the automated one-purpose machines designed especially for the radiator core assembly process. These machines are equipped with all the necessary drives, guideways, and tools to be used in any production of the radiator cores. Primary use of these machines is in the series production of the radiator cores. These machines have large disadvantages that they are complicated to set, maintain, and have big outer dimensions which can be a problem for small workshops.

Main problematic construction areas of the original assembly device construction are guideways of the movable stoppers, drive of the movable stoppers, and the lack of space for mounting additional guideways to be used for another assembly operation. Generally, the original assembly device is missing a mechanism to be adjusted to a certain radiator core dimension.

The guideways of the assembly device should allow smooth, effortless, and continuous movement. It should precisely help to move the required parts of the device and allow it to transfer necessary forces to perform all the needed operations of the assembly process.

The drive of the movable stoppers should be unified or replaced by a single component. The pressing operation should be done in one motion and not prolong the time of the pressing operation. The construction design should allow a specific distance between the stoppers to fit the actual radiator core.

The base or base frame of the assembly device should be designed in a way that allows it to perform other operations of the assembly process like pressing the header plates and breaking the ends of the cooling tubes.

6.2 MASTER'S THESIS GOALS

The main goal of this thesis is to create a functioning design of the assembly device used in prototype production of radiator cores. The new design should implement the concept of the original assembly device and improve it so it would meet several requirements described below and as a result be successfully accepted into the prototype production process.

The new radiator core assembly device should be design in way that the next parameters are fulfilled:

- The new design must be universal for horizontal radiator cores with a single row construction.
- It should be simple to use and lower the risk of wasters during the prototype production.
- The maximum permissible number of cooling tubes inserted into the assembly device is 60.
- The maximal permissible length of the radiator tubes is 700 mm.
- The maximum height of the cooling tube is 25,2 mm.
- The maximal thickness of the radiator cooling tube is 2,2 mm.
- The maximal thickness of the radiator fin is 5,55 mm.
- For a single row construction of the radiator core, required force for one header plate pressing is 4289 N.
- For a single row construction of the radiator core, required force for pressing the radiator core composition to a demanded dimension is 2000 N.
- The radiator cooling tube must be pressed into the header plate with approximately 7 mm overlap.
- The new design of the radiator core assembly device must have enough space for the placing of the brazing frame.

The main requirement is to increase the efficiency of the assembly process. This requirement will be considered the most in choosing the assembly device type so all the necessary operations of the assembly process can be done with the new design of the assembly device and possibly no accessory tools or equipment is needed. As much as possible of the unnecessary delays during the assembly process should be prevented with the new design. The operator should be able to operate this new design of the assembly device with minimum skills and experience and still achieve perfect results. The new design should be simple to control and adjust to specific radiator core dimensions. The assembly strategy of the radiator core performed in the new assembly device should shorten the assembly and contribute to the increase of efficiency. The requirement is that the new design of the assembly device should allow easy maintenance of all moving parts. Since the assembly process does not generate an excessive amount of dust or debris this requirement will not be critical in the design process.

7 CONCEPTUAL DESIGN

Before the new design of the assembly device can be made, firstly it is important to create a solution for critical areas of the design according to the previous chapter and create the whole conception of the assembly device.

There are two possible solutions of the new assembly device considering the assembly device assignment. First conceptual design of the assembly device will be manually operated, and the second conceptual design of the assembly device will be evaluated in terms of how they can increase efficiency of the assembly process, simplicity, and versatility.

To make sure the final selected conceptual design is going to work and function properly according to the requirements in the previous chapter the critical areas of the assembly device construction need to be correctly selected and designed. Several solutions and construction variants will be designed and compared with the focus on fulfilling the assignment described in the previous chapter. Main critical areas are the base frame and main plate, movable stoppers, complete adjustment for specific radiator core, pressing and breaking operation.

7.1 THE FIRST CONCEPTUAL DESIGN

The first conceptual design is manually operated. The biggest flaw of the original design of the radiator core assembly device was that it did not allow the header plate pressing operation and it was not adjustable in the x-axis to exact radiator core width. To incorporate solutions of these flaws into the new design the new assembly device is constructed almost like the original design. The main plate of the new design is replaced by five smaller main plates. The 3rd or middle main plate is fixed, and the rest of these plates are moving according to the setting of the length of the radiator. These plates are similar as the original design firm stoppers and movable stoppers. The movable stoppers are also driven by ball screws supported in bearing housings mounted on the back side of these main plates. Another disadvantage of the original design is that each of the ball screws must be operated individually and that prolongs the assembly time. The new design of the radiator core assembly device uses a central spline shaft to connect all the ball screws. Each one end of the ball screw has a machined slot for the shaft key. Together with the shaft key the ball screws are connected to a worm gear which is powered by the spline shaft. The spline allows each main plate with all attached components to move in the direction of the x-axis and thus adjusting the length of the exact radiator. By turning the central spline shaft, it is much easier for the operator to perform the pressing operation of the radiator core composition. The correct dimension is achieved by a ruler engraved to the central main plate. The operator would simply check the desired pressing dimension on the ruler and stop the pressing when the required dimension is achieved. These five main plates are mounted on two supporting rails. The main plate is connected to the supporting rail with ball bearing blocks. These blocks are on each side of the main plate which are allowing the main plate its movement in the x-axis. These complete main plates with stoppers, ball screws and sprockets create 5 modules. To ensure the movement of non-fixed modules they are connected by a scissor mechanism and connected through a nut to a central ball screw. This ball screw has machined end to a hexagon shape prepared to be turned over by a crank with handle. Side modules (left or right) have prepared mounting spots for linear guideways which are used for pressing the header plates or the breaking operation of the cooling tubes.

After simple testing of the radiator fins and discussion with the management of the R&D department of Hanon Systems Autopal Services s.r.o. in Hluk this solution is not possible. The biggest issue found in this assembly device design is the support of the radiator fins. The radiator fins are made from a very thin sheet of aluminium. Their characteristic quality is that they do not tend to hold shape very well. If the operator inserts the radiator fins into this assembly device the radiator fins would simply fall through or negatively deform during the assembly process. This design allows the operator to negatively deform the radiator core. Solution to this problem would be to create a retractable thin plate mounted between each of the modules and mounting some adjustable stop blocks for the pressing operation. Another solution would be to transfer the stop board used in the original assembly device design.

The picture below represents the pressing mechanism of the first conceptual design and the base frame. Due to the described circumstances the conceptual design was then stopped.

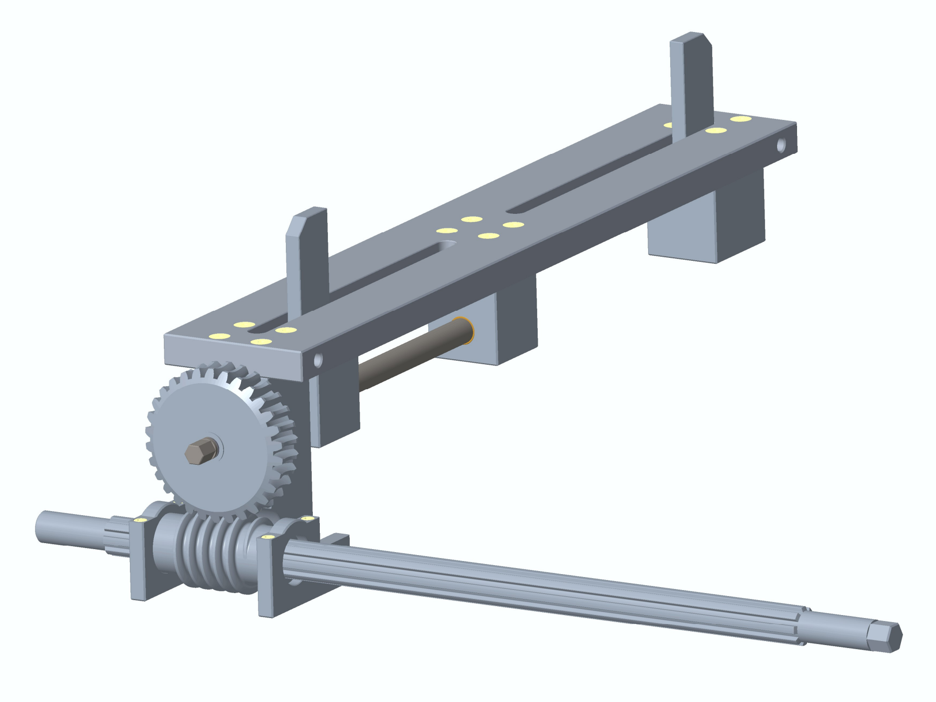

Figure 11 The pressing mechanism of the first conceptual design

7.2 THE SECOND CONCEPTUAL DESIGN

To address the issues made in the first conceptual design firstly it is important to rethink the assembly device type. The second conceptual design of the assembly device needs to reduce the use of other tools in the assembly process like the stop board or the breaking tool. Also, the possible human error of the operator must be eliminated in the new conceptual design.

The second conceptual design was selected to be partially automated instead of manually operated. The base plate of the second assembly device is mounted on the base frame which is placed on the working table. The base plate is tilted at a 15 ° angle from the base frame.

To address the issue of adjustment in the direction of the x-axis to the length of the radiator, the main work plate has fixed dimensions. It is machined to a precise dimension for the concrete radiator type. This solution removes the problem with the radiator fins' negative deformation or falling between the main plates of the first conceptual design. On the base plate are 2 pairs of linear guideways with 1 ball bearing blocks per side. The guideways are made by HIWIN, series EGH 30 CA in length of 1350 mm. On these ball bearing blocks are mounted 2 joining arms or called connecting “bridge”. These 2 bridges hold the pneumatic cylinders carrying tools used for the pressing and positioning operation. To help with coping with the opposite force and the stress from the pressing operation the ball bearing blocks are stopped in required position by 2 pneumatic clamps PMK30-2 made by HIWIN per side with combined clamping force of 3500 N per side of the bridge. The bridge is holding 2 pneumatic cylinders NSKU-100-100-F made by STASTO with a stroke of 100 mm and pushing force of 4710 N at 6 bars (g). On the pneumatic cylinders is a mounted tool holder with a dovetail keyway which is holding the actual tool. First tool is the positioning tool, which has machined grooves on its side. The side of the positioning tool consists of “comb” with height of 20 mm and width of 3 mm designed precisely so only one cooling tube can fit in the groove. The length of the groove is 7 mm, so it precisely positions the radiator fins in the radiator core. The second tool is the pressing tool, and it has a machined face in shape of the correct header plate which is secured in the pressing tool with 4 spring plungers. The third tool is the breaking tool which has pins designed to fit the inside of the cooling tubes. The tools are secured in the tool holder with a simple screw. [29] [30] [31]

On the main plate there is also another pair of linear guideways with 2 ball bearing blocks per side for movement in the direction of the y-axis. The guideways are made by HIWIN, series EGH 30 CA in 600 mm. On these ball bearing blocks is mounted a joined base plate with support rails. On this joined base plate is mounted another pneumatic cylinder NSKU-100-100-F made by STASTO with a stroke of 100 mm and pushing force of 4710 N at 6 bars (g). This pneumatic cylinder is creating the needed pressure to successfully achieve the pressing operation to the correct dimension. The movable stoppers are created by one single part which is an essentially small beam. This beam is secured by 2 linear shafts with an outer diameter of 16 mm. [29] [31]

To set the precise working position of each bridge there are used 2 stepper motors AS5918 made by NANOTEC. The stepper motors are connected via shaft flexible coupling to the ball screw. Both ends of each ball screw are mounted into the ball screw bearing housing which are bolted to the main plate of the assembly device. The base of the bridges includes a hole for the ball flange nut which is bolted to the base of the bridge. Each stepper motor is attached to the main plate with two bolts. [32]

Similarly, as the x-axis the assembly mounted on the linear guideways movable in the direction of y-axis is driven through a one stepper motor AS5918 made by NANOTEC. Same as the layout in the x-axis the stepper motor is connected via shaft flexible coupling to one central ball screw. Both ends of each ball screw are mounted into the ball screw bearing housing which are bolted to the main plate of the assembly device. The base of the assembly movable in the direction of the y-axis has a hole for the ball flange nut which is bolted to the base of the assembly. Also, the central stepper motor for the y-axis is attached to the main plate with two bolts. [32]

The picture below represents the second conceptual design of the assembly device without the base frame.

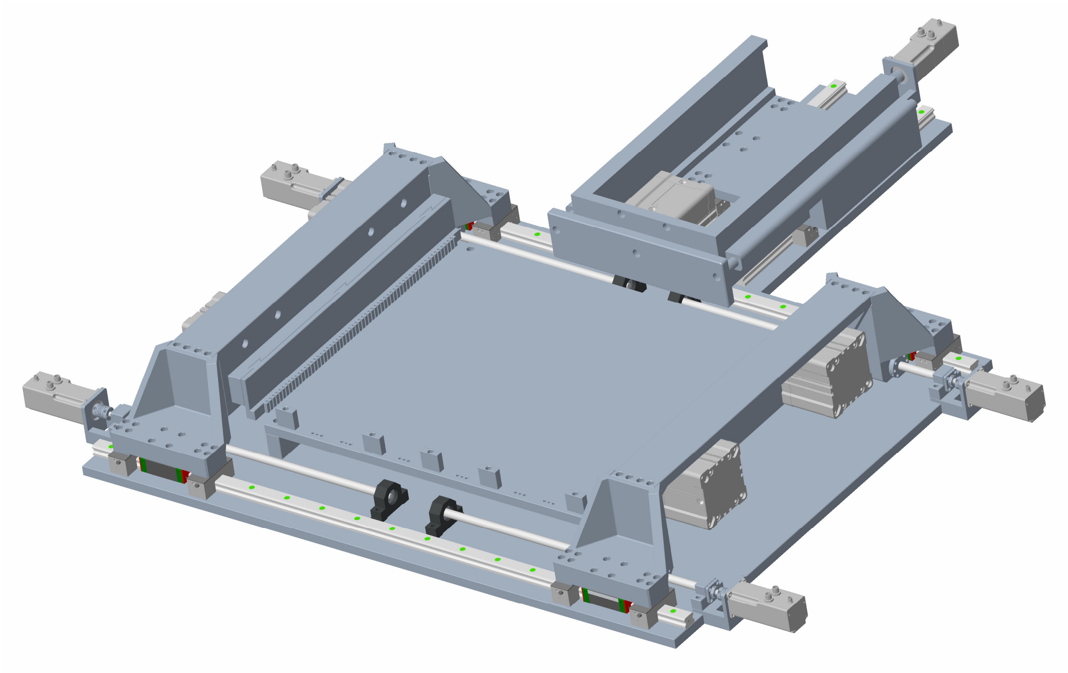

Figure 12 The simplified second conceptual design

7.3 THE BASE FRAME AND MAIN PLATE

The material used for the base frame and the main plate should be light, provide necessary strength and should not be too expensive. The first option can be aluminium alloy for example EN AW 6082 T6 which has great weldability and machinability, yield strength of 240 MPa with density of 2700 kg/m^3. [33] Second option can be non-alloy structural steel, which has great weldability and machinability, minimum yield strength of 225 MPa with density of 7850 kg/m^3. [34] First material option is light with good mechanical properties, but is it more expensive than second option, which is cheaper, has good mechanical properties but much heavier.

7.3.1 THE MAIN PLATE

The main plate can be made from solid piece or as several segments. Advantage of the main plate made from solid piece is that there is no risk of negative deformation of the radiator fins because they are supported in all their length. Disadvantage of this solution is higher manufacturing costs and weight compared to the segment design of the main plate. Another disadvantage is that if the main plate is made from a single piece, it must be manufactured for the exact length of the radiator core or possibly for a small range of lengths of radiator cores and this only increases the manufacturing costs. The segment design allows the segments to be positioned according to the size of the length of the radiator core and thus are more versatile. Huge disadvantage is that the gaps which are created between the segments must be covered otherwise the radiator fins can fall through or negatively deform. Also, the covers must be adjustable to the size of the gap and that might create another excessively complicated mechanism.

7.3.2 THE BASE FRAME

The base frame could be made from solid piece and should be large enough to allow mounting all the necessary components of the assembly device, have good mechanical properties and strength. Additionally, the design of the main plate should include anchoring holes for possible mounting the base frame to the working table. Material of the base frame could be also aluminium alloy or non-alloy structural steel.

7.4 MOVABLE STOPPERS

The pressing operation to correct dimension is crucial for performing following operations on the assembly process successfully. The focus is on the mechanism design of the stoppers, so the pressing motion is unified for all the stoppers and the required force of 2000 N is achieved.

7.4.1 CENTRAL STOPPER

One solution is to replace the five stoppers with one central part (central stropper) which can be replaceable in case there was reason to change the size of the central stopper. The pressing force would be achieved with a pneumatic cylinder and the position adjustment for the specific radiator core would be achieved with this pressing assembly mounted on linear guideways driven by a ball screw which is turned by a stepper motor. This solution provides great pressing force since there is a great variety of pneumatic cylinders available on the market, it is fully adjustable, so it covers every width of the radiator according to the assignment.

7.4.2 FIVE SEPARATE STOPPERS

Another possible solution is to design the stoppers separately but included in the main plate segment design, so it allows great adjustability for the specific length of the radiator core, there are no linear guideways which decreases the costs of the assembly device. On the other hand, this solution does not allow the variability as the central stopper and that is one of the main requirements on the new assembly device design.

7.5 LENGTH ADJUSTMENT FOR SPECIFIC RADIATOR CORE

The length adjustment in direction of the x-axis is the same for the conceptual designs. The adjustment is provided by linear guideways mounted on the base frame. For both conceptual designs on the linear guideways are mounted linear ball bearing blocks which hold either the connecting bridges or the separate segments. This type of linear guideways has low difference between the static coefficient of friction and the dynamic coefficient of friction which provides smooth and sturdy guidance, can transfer enormous forces during its operation and are well designed in the presence of dust or debris with additional greasing points to allow long-term and trouble-free operation.

7.6 PRESSING AND BREAKING OPERATION

7.6.1 THE MANUALLY OPERATED PRESSING AND BREAKING

The pressing and breaking operation can be done manually with the use of a mechanism using levers to achieve the required pressing or breaking force. Since the pressing force is significantly high the mechanism can be quite complicated and can include several components which have to be designed correctly. The large number of components increases the risk of failure and potential maintenance. Also, the number of manually operated actions creates demands on the skills of the human operator.

7.6.2 THE AUTOMATICALLY OPERATED PRESSING AND BREAKING

The automated operations of pressing and breaking have one enormous advantage. The use of linear guideways simplifies the whole construction and allows it to adapt to specific lengths of radiator core. Also, since the process is set programmed the risk of human error is lower and the operator with minimum skills can achieve the same result every time.

8 CONSTRUCTION DESIGN

For the final construction design the second conceptual design was selected. The main goal of the new assembly device is to increase the efficiency of the radiator core assembly process. The second conceptual design does meet this requirement the best.

The second conceptual design is partially automated and leaving the operator only to insert the radiator core components into the device and activate each of the assembly processes. This design helps to rapidly shorten the assembly time, ensures the same quality of every radiator core assembled in this device and brings the prototype production closer to the series production.

The second conceptual design fulfils all the requirements defined in the assignment. Since it is partially automated, with core components like drives and guideways, it is versatile and can be modified to fulfil different tasks of the assembly process which is making the assembly device more universal.

Considering the size and the goal of this thesis the control cabinet including the control components for the stepper motors and pneumatic cylinders will not be described and designed in this thesis. The main goal of this design is to present a functional solution with focus on the mechanism rather than the additional components.

The 3D models of components like ball bearing blocks, linear guideways, pneumatic clamps, ball screws, ball flange nut, supporting housings, stepper motor and pneumatic cylinders used in the construction design are available to the public at manufacturers web pages. [29] [30] [31] [32] [35] [36]

The picture below represents the final construction design together with the base frame.

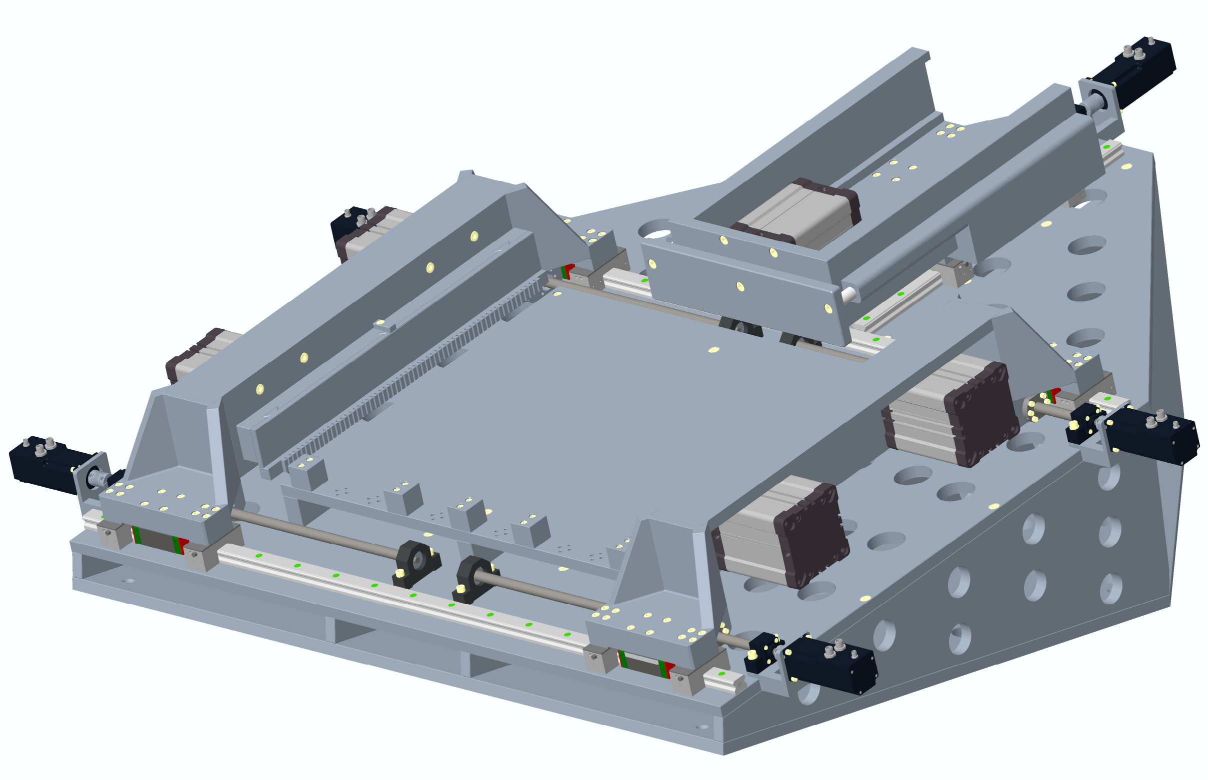

Figure 13 The final construction design

8.1 THE BASE FRAME AND MAIN PLATE

The base frame and main plate are designed from aluminium alloy EN AW 6082 T6. This material was selected because of its good mechanical properties, and it is also very light [33].

The main plate was selected to be made from a solid piece of material. This solution means that in case of different lengths of the radiator core the main plate must be manufactured and mounted into the assembly device. Nevertheless, this solution ensures support under the radiator fins which is a far more critical factor. Also, the solid main plate does simplify the design since there is no adjusting mechanism for the segment plates.

Same as the main plate the base frame is made from a solid piece of material and ensures enough mounting space for all the necessary components. At the corners of the base frame there are anchoring holes for possible anchoring to the working table.

8.2 MOVABLE STOPPERS

For the design of the movable stoppers was selected the central stopper. This design is universal for the radiator core lengths and possibly can be replaced with a stopper with alternate dimensions. The central stopper is activated through a pneumatic cylinder and together with the pneumatic cylinder they are mounted on the base frame. The base frame is mounted on ball bearing blocks with linear guideways which allow adjustment to specific width of the radiator core. The whole assembly with the central stopper is driven by a ball screw which is turned by a stepper motor.

8.3 Length adjustment for specific radiator core

The length adjustment is provided in a way as it was already mentioned in chapter 7.5.

8.4 Pressing and breaking operation

Because of the design of connecting bridges and the length adjustment the pressing and breaking operations will be performed automatically. Again, this solution increases the efficiency of the assembly process, minimises the risk of human error and possible waster and ensures successfully performing both operations for every assembly process of the radiator core.

8.5 Calculations

Several components in the construction design must be checked and evaluated if they are designed correctly. Firstly, the firm stoppers must be checked, if the two-bolt design can withstand the forces created in the operation of the pressing to correct dimension. Then the linear guideways together with the ball bearing blocks and pneumatic clamps need to be checked. It is also important to consider the suitability of the used ball screws. Finally, the overall structural check of the connecting bridges together with the pressing assembly need to be performed.

8.5.1 Firm stoppers

Firm stoppers are loaded with force created by the operation of the pressing to the correct dimension which is 2000 N. This force is distributed into five firm stoppers which have dimensions of 40 x 40 x 38 mm. This equals to force of 400 N loading the one stopper. The firm stopper will be checked as a force joint.

The picture below shows the location of the firm stoppers.

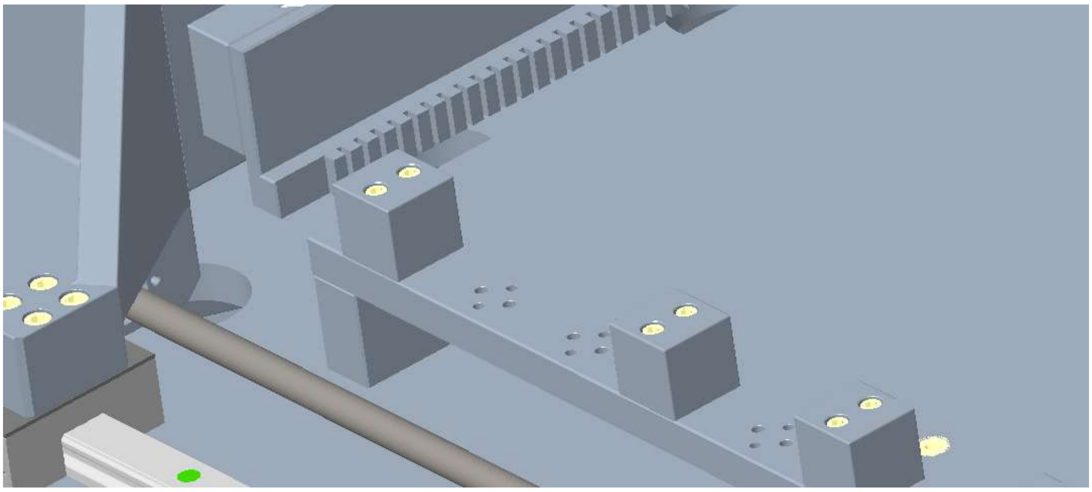

Figure 14 The firm stoppers mounted on the main plate

Calculation parameters:

- Selected bolts for mounting the firm stopper: Hexagon socket head cap screw ISO 4762 – M6x45 - 8.8 Zinc-plated
- Pitch: $p = 1\ mm$ [34]
- Thread angle: $\alpha = 60\ °$ [34]
- Number of bolts: $N = 2$
- Fastener diameter: $d = 6\ mm$
- Fastener hole: $d_h = 7\ mm$ [34]
- Fastener length: $\mathrm{L} = 45\ mm$
- Threaded length: $L_T = 24\ mm$ [37]
- Fastener head diameter: $d_b = 10\ mm$ [37]
- Area of threaded portion: $A_t = 20{,}1\ mm^2$ [34]
- First material thickness: $h = 31\ mm$
- Second material thickness: $t_2 = 20\ mm$
- External load per bolt applied perpendicularly to the bolt axis on one firm stopper: $P = \frac{2000}{5} = 400\ N$
- Half-apex angle of general cone geometry: $\alpha_c = 30\ °$ [34]
- Elastics Modulus of fasteners: $E_F = 207\ GPa$ [34]
- Elastics Modulus of aluminium: $E_{AL} = 71{,}7\ GPa$ [34]
- Minimum Proof Strength of selected fastener: $S_p = 580\ MPa$ [34]
- Minimum Yield Strength of selected fastener: $R_{p0{,}2b} = 640\ MPa$ [34]
- Maximal permissible Screw Bearing Pressure: $p_{bmax} = 150\ MPa$ [34]
- Friction coefficient between different surfaces of bolted connections for surfaces without any surface finish: $f = 0{,}2$ [34]
- Friction coefficient dependent upon the surface smoothness, accuracy, and degree of lubrication: $f = f_c = 0{,}15$ [34]

Calculations:

Check of fastener length [34]:

$$L > h + 1{,}5d = 31 + 1{,}5\ 6 = 40\ mm \tag{2}$$

Round up to selected fastener length [34]:

$$L = 45\ mm$$

Length of unthreaded portion in grip [34]:

$$l_d = L - L_T = 45 - 24 = 21\ mm \tag{3}$$

Since the second material thickness is bigger than the fastener diameter, the grip length [34]:

$$l = h + \frac{d}{2} = 31 + \frac{6}{2} = 34\ mm \tag{4}$$

Length of threaded portion in grip [34]:

$$l_t = l - l_d = 34 - 21 = 13\ mm \tag{5}$$

The area of unthreaded portion [34]:

$$A_d = \pi \frac{d^2}{4} = \pi \frac{6^2}{4} = 28{,}274\ mm^2 \tag{6}$$

Fastener stiffness [34]:

$$k_b = \frac{A_d A_t E}{A_d l_t + A_t l_d} = \frac{28{,}274\ 20{,}1\ 207\ 10^3}{28{,}274\ 13 + 20{,}1\ 21} = 148{,}976\ \frac{kN}{mm} \tag{7}$$

Members stiffness:

The compression of a member with the equivalent elastic properties is represented by a frustum of a hollow cone and it is composed of three members. For each member must be calculated its cone diameter and length:

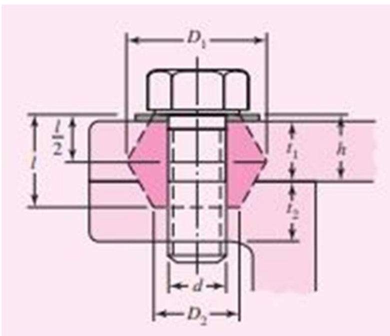

Figure 15 Pressure-cone frustum member model for a cap screw [44]

Calculation of member stiffness k_{m1} [34]:

$$D_1 = d_b = 10\ mm \tag{8}$$

$$t_1 = \frac{l}{2} = 17\ mm \tag{9}$$

$$k_{m1} = \frac{0.5774\ \pi\ E_{AL}\ d}{\ln\left(\frac{1.155\ t_1 + D_1 - d)(D_1 + d)}{1.155\ t_1 + D_1 + d)(D_1 - d)}\right)} = \tag{10}$$

$$k_{m1} = \frac{0.5774\ \pi\ 71700\ 6}{\ln\left(\frac{1.155\ 17 + 10 - 6)(10 + 6)}{1.155\ 17 + 10 + 6)(10 - 6)}\right)} = 0{,}8\frac{MN}{mm} \tag{10}$$

Calculation of member stiffness k_{m2} [34]:

Firstly, it is necessary to calculate t_3 to be able to calculate t_{22} (parameter labelled t_{22} to avoid exchange for parameter t_2).

$$t_3 = l - h = 34 - 31 = 3\ mm \tag{11}$$

$$D_2 = D_1 + 2\ t_3 \tan(\alpha_c) = 13{,}464\ mm \tag{12}$$

$$t_{22} = \frac{l}{2} - t_3 = 14\ mm \tag{13}$$

$$k_{m2} = \frac{0.5774\ \pi\ E_{AL}\ d}{\ln\left(\frac{1.155\ t_{22} + D_2 - d)(D_2 + d)}{1.155\ t_{22} + D_2 + d)(D_2 - d)}\right)} \tag{14}$$

$$k_{m2} = \frac{0.5774\ \pi\ 71700\ 6}{\ln\left(\frac{1.155\ 14 + 13{,}464 - 6)(13{,}464 + 6)}{1.155\ 14 + 13{,}464 + 6)(13{,}464 - 6)}\right)} = 1{,}424\frac{MN}{mm} \tag{14}$$

Calculation of member stiffness k_{m3} [34]:

$$D_3 = D_1 = 10\ mm \tag{15}$$

$$t_3 = 3\ mm \tag{11}$$

$$k_{m3} = \frac{0.5774\ \pi\ E_{AL}\ d}{\ln\left(\frac{1.155\ t_3 + D_3 - d)(D_3 + d)}{1.155\ t_3 + D_3 + d)(D_3 - d)}\right)} \tag{16}$$

$$k_{m3} = \frac{0.5774\ \pi\ 71700\ 6}{\ln\left(\frac{1.155\ 3 + 10 - 6)(10 + 6)}{1.155\ 3 + 10 + 6)(10 - 6)}\right)} = 1{,}824\frac{MN}{mm} \tag{17}$$

Calculation of total member stiffness k_m [34]:

$$k_m = \frac{1}{\frac{1}{\mathrm{k}_{m1}} + \frac{1}{\mathrm{k}_{m2}} + \frac{1}{\mathrm{k}_{m3}}} = \frac{1}{\frac{1}{0{,}8} + \frac{1}{1{,}424} + \frac{1}{1{,}824}} = 0{,}400\,\frac{MN}{mm} = 399{,}889\,\frac{kN}{mm} \quad (18)$$

Calculating the stiffness constant of the joint [34]:

$$C = \frac{k_b}{k_b + k_m} = \frac{148{,}976}{148{,}976 + 399{,}889} = 0{,}271 \quad (19)$$

Considering the nature of the joint the load factor was selected:

$n_L = 3$

Condition of friction joint [34]:

The frictional force in the joint must be higher than the load force [34].

$$F_f = F_i\, f_c \geq \frac{n_L\, P}{N} \quad (20)$$

$$F_i \geq \frac{n_L\, P}{N\, f_c} = \frac{3\ 400}{2\ 0{,}15} = 3000\ N \quad (21)$$

The minimum preload F_i is 3000 N to maintain the load factor n_L equals the selected value of 3.

Calculation of the torque necessary to develop the preload [34]:

Firstly, must be calculated the pitch and minor diameter, mean collar diameter and height of external threads.

Height of external threads [34]:

$$H = \frac{\sqrt{3}}{2}\, p = \frac{\sqrt{3}}{2}\, 1 = 0{,}866\, mm \quad (22)$$

Pitch diameter [34]:

$$d_p = d - \frac{3}{4} H = 6 - \frac{3}{4}\, 0{,}866 = 5{,}35\, mm \quad (23)$$

Minor diameter [34]:

$$d_r = d - \frac{17}{12} H = 6 - \frac{17}{12}\, 0{,}866 = 4{,}773\, mm \quad (24)$$

Mean collar diameter [34]:

$$d_c = \frac{d_b + d_h}{2} = \frac{10 + 7}{2} = 8{,}5\, mm \quad (25)$$

Calculation of torque required to produce a given preload which is consisting of torque required to overcome the friction in the threads and friction on the collar face [34]:

$$T = T_t + T_c = \frac{F_i\, d_p}{2}\left(\frac{p + \pi\, f\, d_p \sec\left(\frac{\alpha}{2}\right)}{\pi\, d_p - f\, p \sec\left(\frac{\alpha}{2}\right)}\right) + \frac{F_i\, f_c\, d_c}{2} \tag{26}$$

$$T = T_t + T_c = \frac{3000\ 5{,}35}{2}\left(\frac{1 + \pi\ 0{,}15\ 5{,}35 \sec\left(\frac{60}{2}\right)}{\pi\ 5{,}35 - 0{,}15\ 1 \sec\left(\frac{60}{2}\right)}\right) + \frac{3000\ 0{,}15\ 8{,}5}{2} \tag{26}$$

$$T_t = 1{,}887\ Nm \tag{26}$$

$$T_c = 1{,}913\ Nm \tag{26}$$

$$T = T_t + T_c = 1{,}887 + 1{,}913 = 3{,}8\ Nm \tag{26}$$

Calculation of preload stress [34]:

$$\sigma_i = \frac{F_i}{A_t} = \frac{3000}{20{,}1} = 149{,}524\ MPa \tag{27}$$

Calculation of shear stress [34]:

$$\tau = \frac{16\, T_t}{\pi\, d_r^3} = \frac{16\ 1{,}887}{\pi\ 4{,}773^3} = 88{,}376\ MPa \tag{28}$$

Calculation of equivalent stress according to HMH [34]:

$$\sigma_{HMH} = \sqrt{{\sigma_i}^2 + 3\,\tau^2} = \sqrt{149{,}524^2 + 3\ 88{,}376^{\ 2}} = 213{,}793\ MPa \tag{29}$$

Calculation of the safety factor [34]:

$$n_p = \frac{R_{p0,2b}}{\sigma_{HMH}} = \frac{640}{213{,}793} = 2{,}994 \tag{30}$$

Calculation of Screw Bearing Pressure:

The fastener is threaded 14 mm inside the second material and with pitch 1 mm equals to 14 threads inside the second material.

$$N_t = 14$$

Minor nut diameter [34]:

$$D_r = d - \frac{10}{8} H = 6 - \frac{10}{8}\ 0{,}866 = 4{,}917\ mm \tag{31}$$

$$p_b = \frac{F_i}{N_t \frac{\pi}{4} (d^2 - D_r^2)} = \frac{3000}{14 \frac{\pi}{4} (6^2 - 4{,}917^2)} = 23{,}086\ MPa \quad (32)$$

$$p_b < p_{bmax} \quad (33)$$

Screw Bearing Pressure in the threads of the joint is lower than maximal permissible Screw Bearing Pressure.

8.5.2 LINEAR GUIDEWAYS

The selected linear guideways are loaded with forces during the header plate pressing operation as well as during the breaking operation. The required pressing force for one header plate is 4289 N and it is distributed between the two ball bearing blocks mounted on linear guideways.

Linear guideways used in constructional design were selected with focus on rigidity, smooth movement, low maintenance and compact solution. The linear guideways series EG size 30 are manufactured by company HIWIN and are typically used in automation devices. The linear guideways have high load capacity, only low displacement forces are needed and have great movement efficiency. This specific series is also suitable for applications with low installation space which is ideal for the construction design. The selected bearing blocks are square compact blocks EGH 30 CA with mounting holes located on the top side of the blocks [29].

These blocks can withstand static torque in three axes [29]:

- M_{ox} = 680 Nm
- M_{oy} = 550 Nm
- M_{oz} = 550 Nm

The linear guideway and ball bearing block load is purely static. During the movement of the bearing blocks there is no load present on the bearing blocks except the weight of the connecting bridge with included components. The load on the bearing block is present during the pressing or breaking operation. The force creates a torque with application point in the ball bearing elements. The only load present during the pressing or breaking operation is in the direction of the y-axis.

Loads present in other directions than the y-axis are insignificant.

The picture below shows in detail the mounting position of the ball bearing blocks in the assembly device.

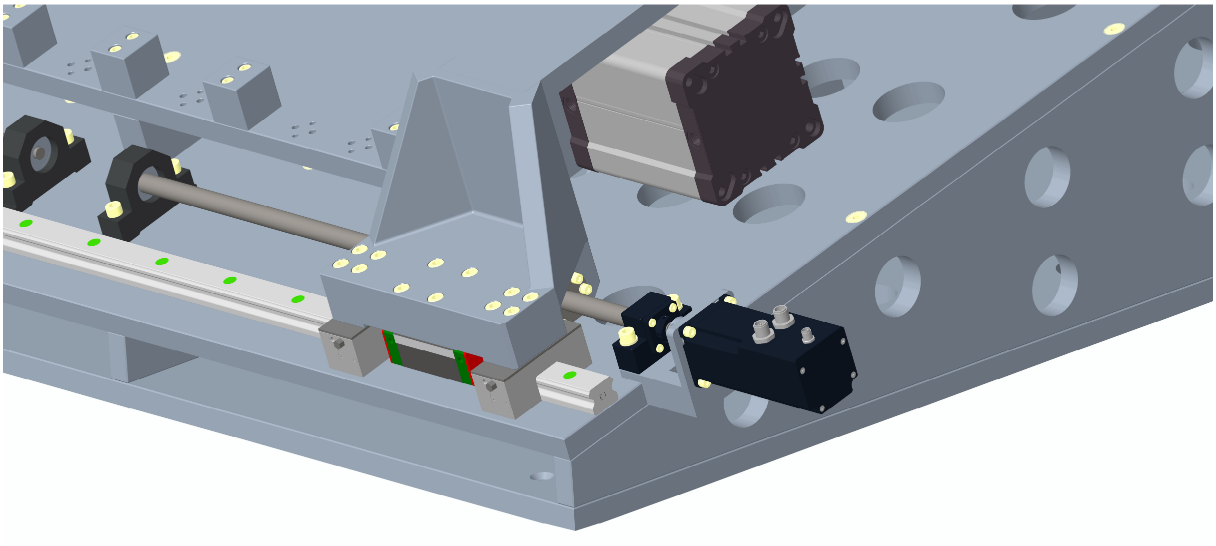

Figure 16 The ball bearing blocks together with the pneumatic clamps mounted on the connecting bridge

Calculation parameters:

- Measured level arm from the centre of the ball bearing elements to the half with of assembled radiator core with cooling tube height of 25,2 mm: $r = 67{,}612$ mm
- External load divided to two bearing blocks: $F = \frac{4289}{2} = 2144{,}5\ N$
- Maximal permissible static torque: $M_{oymax} = M_{oy} = 550\ Nm$ [29]

Calculation of the torque load:

The angle ϴ between the lever arm and the external load is 90°.

$$T = r\ F \sin(\theta) = 67{,}612\ 2144{,}5\ 1 = 145\ Nm \tag{34}$$

$$T\ < M_{oy} \tag{35}$$

The present torque T is lower than maximal permissible static torque M_{oy}.

8.5.3 Pneumatic clamps

For each of the two connecting bridges are used four pneumatic clamps, two for one side. Pneumatic clamps PMK30-2 are made by HIWIN specifically for the linear guideways of series EG and size 30. The pneumatic clamps are in NO configuration (normally open), they are activated only if air pressure is applied. Minimal permissible air pressure is 3 bars (g) and maximal permissible air pressure is 6,5 bars (g). When air pressure is applied to the pneumatic clamp it can provide a holding force of 1750 N [30].

On the pneumatic is applied external force during the pressing and breaking operation of magnitude 4289 N divided into all the pneumatic clamps mounted to one connecting bridge.

Calculation parameters:

Pneumatic clamp holding force: $P_h = 1750\ N$ [30]

External load: $P = \frac{4289}{4} = 1072{,}25\ N$

$$P < P_h \tag{36}$$

The present load P is lower than pneumatic holding force P_h.

8.5.4 BALL SCREWS

The ball screws R16-05T3-FSIDIN made by HIWIN are used for the drive of the connecting bridges and for the pressing assembly. For each connecting bridge two ball screws in length of 655 mm are used for the required position movement. In case of the pressing assembly only one central ball screw in length of 640 mm is used [35].

The ball screw parameters:

- Main screw diameter: $d_{sc} = 16\ mm$ [35]
- Pitch: $p_{sc} = 5\ mm$ [35]
- Used with standard flanged nut
- Non-preloaded and right design

The ball screws used in the construction design are lightly built because they are used only for moving the connecting bridge or the pressing assembly. The ball screw load is to overcome the frictional forces in the linear guideways and the ball bearing blocks, which is insignificant.

8.5.5 LINEAR SHAFTS OF THE PRESSING ASSEMBLY

The operation of the pressing to correct dimension is actuated by a pneumatic cylinder mounted on the pressing assembly. The single pneumatic cylinder must overcome the pressing force of magnitude 2000 N. This force is directed to the central stopper which is supported in sliding casing in the base of the pressing assembly. The central stopper is connected to two linear shafts with an outer diameter of 20 mm. The linear shafts are supported in the sliding casings. The linear shafts are loaded by a static torque created by the pressing force on the level arm from the application point of force which is in the centre of the cooling tubes to the linear shaft axis. After consultation with management of R&D department of Hanon Systems Autopal Services s.r.o. the minimal gap between the moving components and the main plate should be 1 mm. The central stopper is positioned with a 2 mm gap between its lower side of the stopper and the main plate, thus creating maximal 1 mm bending deflection.

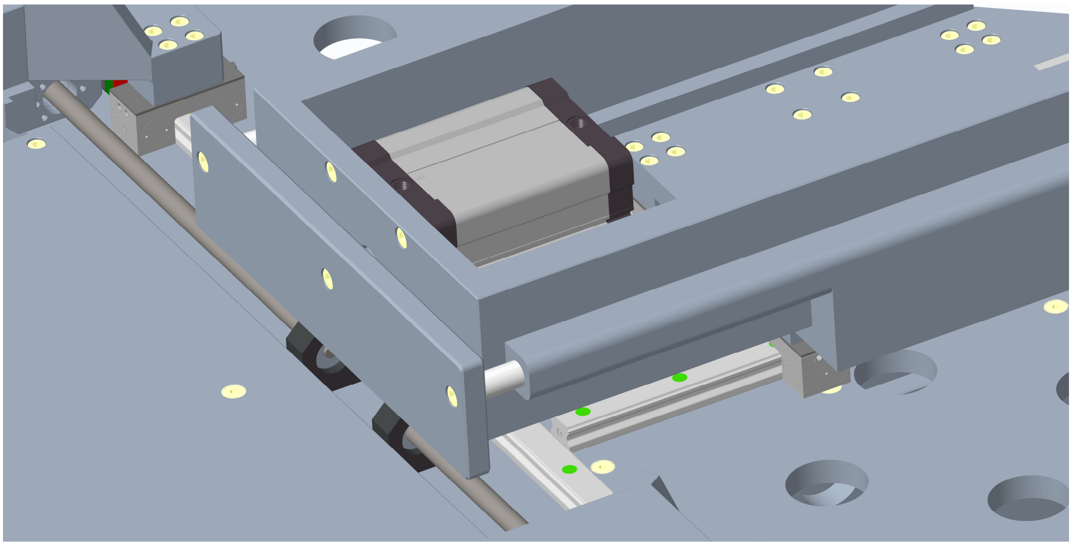

Figure 17 The linear shafts of the pressing assembly supporting the central stopper

Calculation parameters:

- Linear shaft outer diameter: $d_s = 20\ mm$
- Maximal length of the exposed linear shaft: $l_s = 135\ mm$
- Minimum Yield Strength of selected linear shaft: $R_{p0,2s} = 430\ MPa$ [38]
- Elastics Modulus of linear shaft: $E_s = 210\ GPa$ [38]
- External load: $P = \frac{2000}{2} = 1000\ N$
- Selected maximal permissible beam deflection: $y_{perm} = 1\ mm$
- Measured level arm from the centre of the linear axis to the half width of assembled radiator core with cooling tube height of 25,2 mm: $r = 54{,}4$ mm

Calculation:

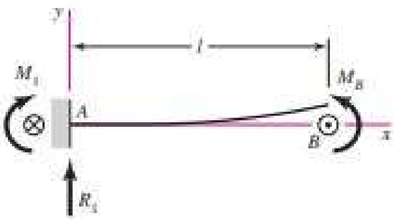

Figure 18 Cantilever with moment load [44]

Calculation of the torque load:

The angle ϴ between the lever arm and the external load is 90°.

$$T = r\ F \sin(\theta) = 54{,}4\ 1000\ 1 = 54{,}4\ Nm \tag{37}$$

Calculation of bending stress:

$$\sigma = \frac{32\ T}{\pi\ {d_s}^3} = \frac{32\ 1000}{\pi\ 20^3} = 69{,}264\ MPa \tag{38}$$

Calculation of the safety factor:

$$n_{p1} = \frac{R_{p0,2}}{\sigma} = \frac{430}{69{,}264} = 6{,}208 \tag{39}$$

Calculating the deflection of the beam:

Calculation of the second moment of area about x-axis:

$$I = \frac{\pi\ d^4}{64} = \frac{\pi\ 20^4}{64} = 7{,}854\ 10^{-9}\ mm^4 \tag{40}$$

Calculation of the beam deflection:

$$y_{max} = \frac{T\ l_s^2}{2\ E_s\ I} = \frac{54{,}4\ 135^2}{2\ 207\ 000\ 7{,}854\ 10^{-9}} = 0{,}301\ mm \tag{41}$$

Calculation of the safety factor:

$$n_{p2} = \frac{y_{perm}}{y_{max}} = \frac{1}{0{,}301} = 3{,}322 \tag{42}$$

8.5.6 CONNECTING BRIDGES

The connecting bridges are loaded with a pressing force of magnitude 4289 N. These forces are transferred through the bodies of the connecting bridges to the bearing blocks and pneumatic clamps. These forces are causing the bridge to deform, and the magnitude of total deformation needs to be checked as well as the maximum value of stress.

The connecting bridge is loaded with the pressing force of 4289 N. This force is divided into two sets of faces and these faces are located under the fastener heads on the connecting bridges. These bolts are connecting the bridges together with pneumatic cylinders.

The bridge is mounted on ball bearing blocks which are mounted on the linear guideways and allow the movement in the direction of the linear guideways. To lock the operating position two pneumatic clamps are installed on both ends of the connecting bridge. Each of the pneumatic clamps have a holding force of 1750 N. These operating conditions are creating the boundary conditions of the static structural analysis performed in software Ansys. Model used for this analysis was simplified by removing unessential curvatures, chambers, and rounds.

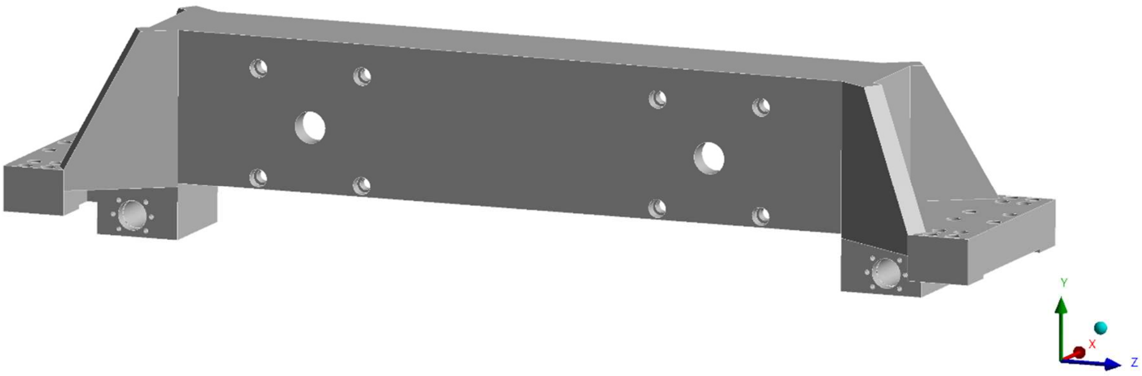

Figure 19 Simplified geometry used in static structural analysis

For performing the total deformation and stress analysis two analysis approaches can be chosen. First approach selects the boundary conditions in following setting:

- Two sets of displacements are selected on faces in contact with ball bearing blocks and the pneumatic clamps. The application faces of the boundary conditions are always selected on both sides of the connecting bridge. First selected boundary condition is displacement with locked motion in the z-axis which is the motion perpendicular to the length of the linear guideways selected on the face in contact with ball bearing blocks. This motion is prevented by the ball bearing elements in the ball bearing blocks. Second selected boundary condition is also displacement in the x-axis and the y-axis selected on the face in contact with pneumatic clamps. Motions in these two axes are prevented by the inner mechanism of pneumatic clamps which is causing the linear guideways to press.

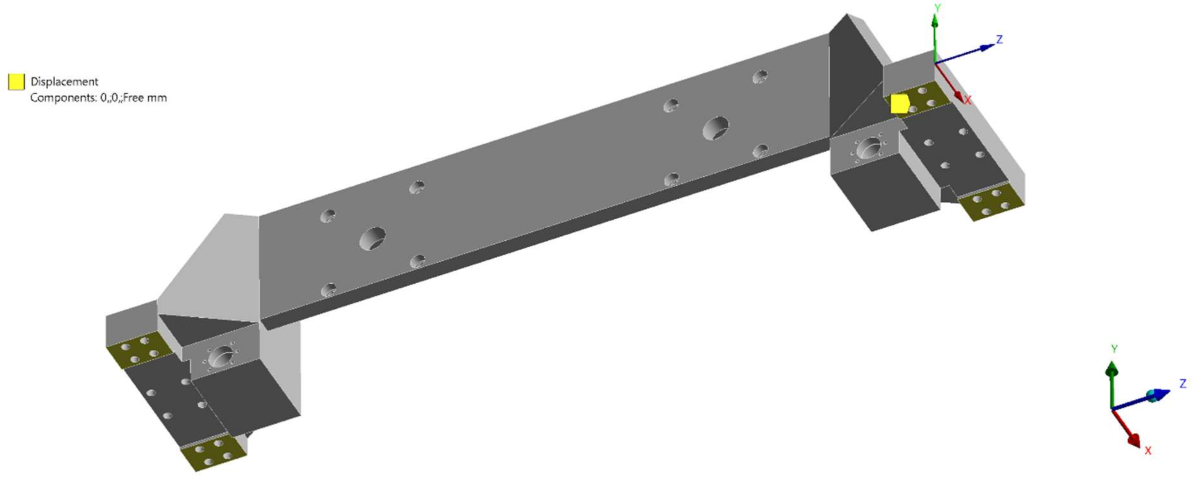

Figure 20 Selection of first displacement application faces (First approach)

- The external load on the bridge is divided by two because of two pneumatic cylinders. The result is two forces with magnitude of 2144,5 N. First force is distributed on four faces under the bolt heads connecting the first pneumatic cylinder. Same conditions were selected also for the second force.

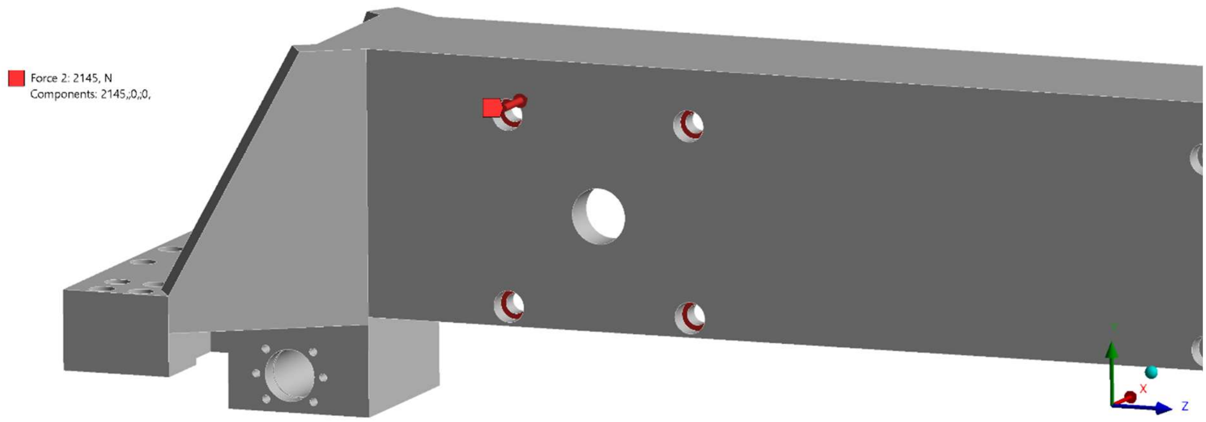

Figure 21 Defining the load application faces (Both approaches)

The mesh of the connecting bridge in the first approach has good element quality with value of 0,713. For this specific mesh were used quadratic type of elements with maximum element size of 5 mm. Other improvements of the created mesh have created problems in calculating the static structural analysis due to exceeding the limit number of elements and nodes in Ansys student version. Failed mesh improvements are using Hex-method on the body of the connecting bridge, splitting the body of the connecting bridge into several segments which are easier to mesh and using sweep-method on the bolt faces. Nevertheless, after inspection the mesh quality of the analysed section of the connecting bridge is overall good and the analysis can continue.

The result of the first approach of the static structural analysis is maximal equivalent stress (von-Mises) 20,933 MPa and maximal deformation of 0,174 mm. The maximal equivalent stress calculated in the analysis is ten times lower than the yield stress of the used connecting bridge material. This result states that the design of the connecting bridge is quite rigid and no problems during the operation of the connecting bridge in the assembly device will be present.

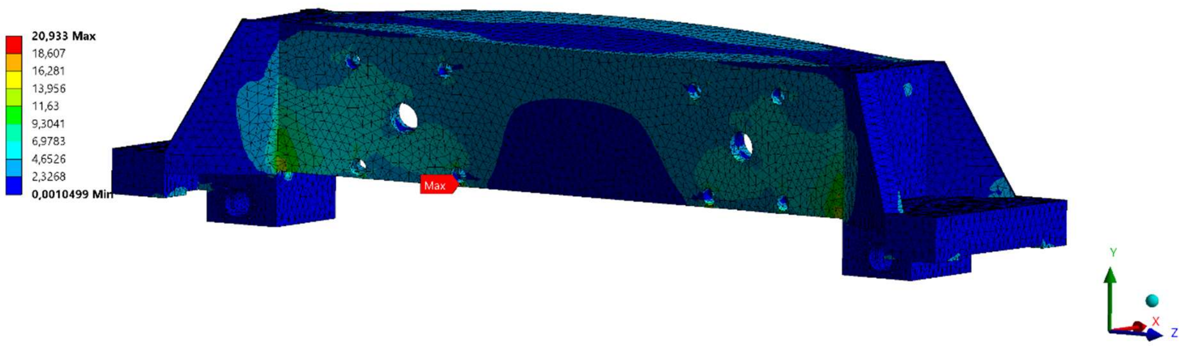

Figure 22 Maximal equivalent stress [MPa] (First approach)

Second and more conservative approach selects the boundary conditions in following setting:

- Three sets of displacements are selected on bolt holes faces in the connecting bridge. Bolts are joining the connecting bridge with ball bearing blocks and the pneumatic clamps. In this approach one pneumatic clamp and linear guideway is considered firm with unlimited stiffness. First selected boundary condition is displacement with locked motion in the x-axis which is the motion in direction of the length of the linear guideways. First boundary condition is selected on the bolt holes faces in contact with pneumatic clamps. This motion is prevented by the inner mechanism of pneumatic clamps which is causing the linear guideways to press. Second selected boundary condition is displacement in the y-axis and preventing the connecting bridge from detaching from the ball bearing blocks. Second boundary condition is selected on the bolt holes faces in contact with ball bearing blocks. Third selected boundary condition is displacement in the z-axis created on only two bolt holes faces in contact with the ball bearing block to allow the connecting bridge to stretch and deform better. Motion in this axis is prevented by ball bearing elements in the ball bearing blocks.

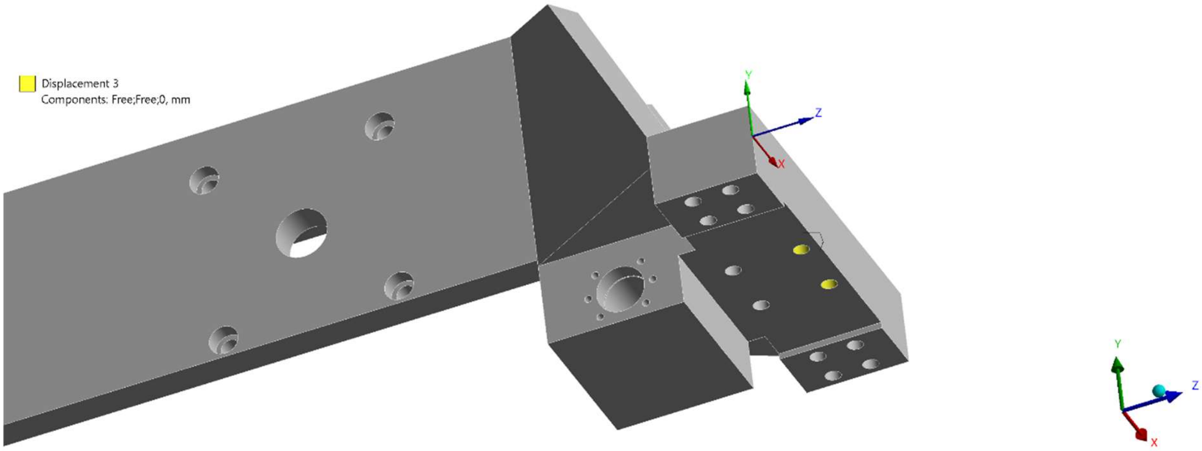

Figure 23 Selection of third displacement application faces (Second approach)

- The external load on the bridge is divided by two because of two pneumatic cylinders. The result is two forces with magnitude of 2144,5 N. First force is distributed on four faces under the bolt heads connecting the first pneumatic cylinder. Same conditions were selected also for the second force.

The mesh of the connecting bridge in the second approach stayed because of the maximum number of elements and nodes the same as in the first approach with good element quality of 0,7138.

The result of the second approach of the static structural analysis is maximal equivalent stress (von-Mises) 52,747 MPa and maximal deformation of 0,235 mm. The maximal equivalent stress calculated in the analysis is approximately four times lower than the yield stress of the used connecting bridge material. This result confirms that the design of the connecting bridge is rigid with necessary strength.

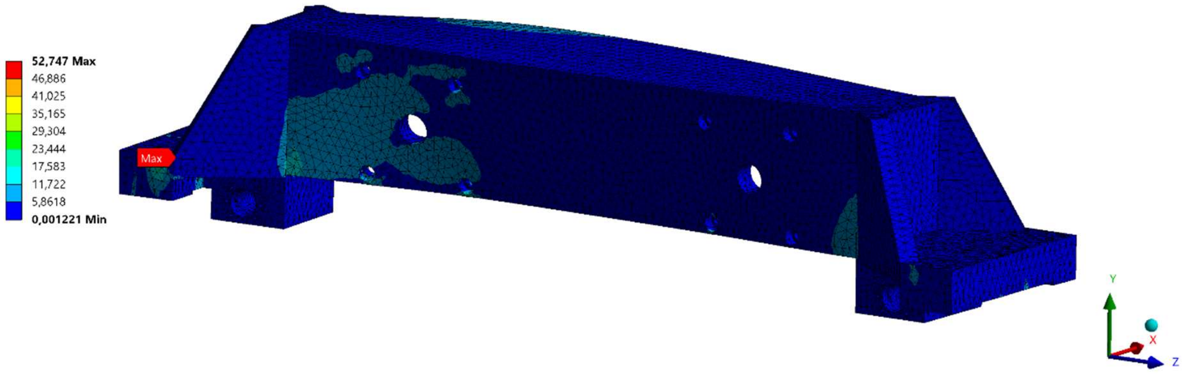

Figure 24 Maximal equivalent stress [MPa] (Second approach)

9 DISCUSSION

The aim of this thesis is to design a new improved assembly device of radiator cores used in prototype production. The construction design of this assembly device is partially automated, and it is created according to the assembly device assignment. The assembly device is designed to help the operator with the assembly process of the radiator core which comprises inserting the cooling tubes and radiator fins into specific locations, performing the operations of synchronised header plates pressing and synchronised cooling tube breaking operation. After this assembly process the assembly device helps to keep pressure on the radiator core composition which allows the operator to place the brazing frame over the radiator core. Main goals of this assembly device are to increase the assembly process efficiency, simplicity and to bring the prototype production closer to series production.

The construction design transfers the manually operated assembly process to automated assembly process. The automated process significantly increases the assembly process efficiency and ensures to maintain the same strength, dimensions, and mechanical parameters for all assembled radiator cores in this device with actual settings. This is the key quality of the construction design.

The approximate outer dimensions of the assembly device are 1742 x 1743 x 647 mm. The dimensions of the assembly device allow the device to be mounted on a working bench and even in a small workshop. Also, it is possible to insert the assembly device into frame together with control cabinet and other necessary components to make the device mobile.

During the design phase of this assembly device several critical areas were found out which could negatively affect the performance of this assembly device. The critical areas were mainly the firm stoppers mounted on the main plate. These stoppers are loaded with force during the pressing operation of the radiator composition. The joint between the stoppers and plate was calculated as a friction joint where the fasteners preload including the required torque was specified. Next the combined stress from the preload and the external load was calculated. These values allowed to calculate the safety factor n_p = 2,994. Finally, the screw bearing pressure in the threads of the joint was compared to the maximal permissible screw bearing pressure. Next the linear guideways were checked if the external torque loading the ball bearing blocks meets the requirements of the manufacturer. The present torque T = 145 Nm is lower than maximal permissible static torque M_{oy} which meets the manufacturer requirements. Subsequently the pneumatic clamps mounted on the connecting bridges and on the pressing assembly were checked if the external force from the pressing or breaking operation is not exceeding the holding force developed by the pneumatic clamps. The external load P = 1072,25 N present on one pneumatic clamp is lower than the pneumatic holding force which complies with the manufacturer’s instructions. Another critical area is the used ball screws. The ball screws used for the position adjustment of the connecting bridges, or the pressing assembly are not significantly loaded. The only force the stepper motor together with flexible coupling and the ball screws are loaded is the frictional force in the ball bearing blocks which has insignificant value. As a result, the ball bearing screws are lightly built, and no further calculation of this area is necessary. In the pressing assembly one critical area is the supporting linear shafts. These linear shafts are loaded with force from the pressing operation. This force divided into one linear shaft creates a loading bending torque which is causing the linear shaft to deflect. The maximum bending stress was calculated and compared to the proof stress of the linear shaft material and as a result the safety factor n_{p1} = 6,208 was calculated. Next the maximal deflection of the linear shaft was calculated and compared to the maximal permissible deflection of the linear shaft. The safety factor comparing the deflections is $n_{p2} = 3{,}322$. Finally, the connecting bridge was analysed.

The static structural analysis performed in the previous chapter in this thesis used two different approaches for setting the boundary conditions to calculate the total deformation and equivalent stress of the connecting bridge. In the first approach the less conservative approach was used by selecting the two displacements of the contact faces between the connecting bridge and the ball bearing blocks and pneumatic clamps. These contact faces of displacements caused that no deformation was possible in the nearby area of these faces which affected the results. The results of the static structural analysis with first approach are total deformation of 0,174 mm and maximal equivalent stress of 20,933 MPa. These values are significantly low and would suggest that the design of the connecting bridge is rigid with high strength. The second more conservative approach used different selections of faces used in the boundary conditions for setting the displacements. Three displacements were selected with bolt holes faces as an application area. First displacement is preventing the motion of the connecting bridge in the direction of the length of the linear guideways. This prevention is achieved by the pneumatic clamps. Second displacement is created on the bolt holes faces for the ball bearing blocks which is preventing the motion in vertical direction. Third displacement is preventing the connecting bridge to move in the direction perpendicular to the linear guideways bud with only two bolt holes faces selected. This displacement allows the connecting bridge to stretch and deform in the z-axis. These selected displacements allowed the connecting bridge to deform around the connecting faces to the ball bearing blocks and pneumatic clamps and create more realistic behaviour of deformation of the connecting bridge in operation. The results of static structural analysis with the second approach are total deformation of 0,235 mm and maximal equivalent stress of 52,747 MPa. The maximal value of equivalent stress is approximately four times lower than the yield strength of the connecting bridge material.

The static structural analysis showed several areas for improvements and future optimization of the connecting bridge design. The static structural analysis showed maximal equivalent stress in the tip of nodes on the bottom side of the connecting bridge. This location suggests that the thickness of material between the bolt head face and the lower side of the connecting bridge could be increased and improve even more the overall strength of the connecting bridge.

The static structural analysis with the second approach showed a maximum equivalent stress on the tip of the nodes on the side section of the connecting bridge where the maximal equivalent stress might be expected and thus confirming the more realistic form of deformation. The first approach of the static structural analysis has calculated the total deformation and equivalent stress with boundary conditions faces and the nearby area as unlimited stiffness which does not correspond to reality. The second approach considers one pneumatic clamp together with linear guideways as firm with unlimited stiffness.

Another improvement which could be done to the connecting bridge is that the base of the connecting bridge be widened and allow creation of another set of bolt holes with the possible mounting of another four pneumatic clamps. These additional clamps would provide necessary holding force in case the assembly device was used for the assembly process of the double row radiator core. In this case and the length and width of the radiator core the twice bigger pressing force would be necessary. With this idea in mind, this assembly device was designed so it is very rigid and durable enough to be adapted to any assembly process of the radiator cores in prototype production.

It is important to mention the external effects of the construction design of the assembly device on the operators and the owner of this device. The function principle of this assembly device is that the correct parameters of individual radiator cores need to be set and adjusted for perfect result. Also, the safety regulations for this automated device are stricter than for the manually operated device which may be a critical issue to comply with for a manufacturer with already existing prototype production.

CONCLUSION

This master's thesis is focused on designing new assembly device of radiator cores used in prototype production. Main goal of this new assembly design is to increase the efficiency of the assembly process and help to bring the prototype production closer to the series production. The new assembly device is designed to assemble the horizontal radiator core with minimal length 300 mm and maximal length 700 mm. The minimal number of cooling tubes in the radiator core composition is 30 and maximal number of cooling tubes is 60.

In the research part of this thesis are described various types of cooling systems together with description of individual components. Focus of the research part of this thesis is on the radiator construction together with related assembly processes and types of assembly devices used in the assembly process. Based on the research part of this thesis two conceptual designs were created together with variant solutions of the critical areas of the designs. From two conceptual designs one was selected, and the critical areas of this construction design were analysed, and their function verified with necessary calculations. Main critical areas were the load on firm stoppers, load of the linear guideways, pneumatic clamps, linear shafts and connecting bridges. The connecting bridges were analysed with focus on the total deformation and their optimization was outlined.

Based on the construction design the assembly drawing of the assembly device was created together with the bill of materials. The concrete details including all production drawings will be created before the manufacturing process of the assembly device in case of approval of this construction design for use in prototype production by Hanon Systems Autopal Services s.r.o.

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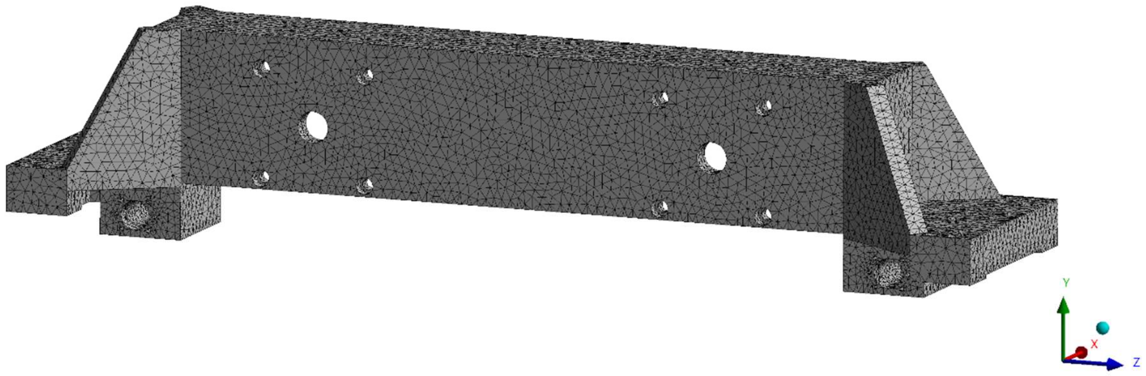
LIST OF ABBREVIATIONS AND SYMBOLS

ΔT	[K]	Temperature change
Δx	[m]	Area thickness
A	[m^2]	Area
A_d	[mm^2]	Area of unthreaded portion
A_t	[mm^2]	Area of threaded portion
C	[–]	Joint stiffness constant
d	[mm]	Fastener diameter
D_1	[mm]	First cone diameter
D_2	[mm]	Second cone diameter
D_3	[mm]	Third cone diameter
d_b	[mm]	Fastener head diameter
d_c	[mm]	Mean collar diameter
d_h	[mm]	Fastener hole diameter
d_p	[mm]	Pitch diameter
d_r	[mm]	Minor diameter
D_r	[mm]	Minor nut diameter
d_s	[mm]	Linear shaft diameter
d_{sc}	[mm]	Ball screw diameter
E_{AL}	[MPa]	Aluminium Elastic Modulus
E_F	[MPa]	Fasteners Elastic Modulus
E_s	[MPa]	Linear shaft Elastic Modulus
f	[–]	Frictional coefficient
f_c	[–]	Frictional coefficient
F_i	[N]	Preload
F_t	[N]	Frictional force
h	[mm]	First material thickness
H	[mm]	External threads height
I	[mm^4]	Second moment of area about x-axis
k	[$W \cdot m^{-1} \cdot K^{-1}$]	Thermal conductivity
k_b	[$kN \cdot mm^{-1}$]	Fastener stiffness
k_m	[$MN \cdot mm^{-1}$]	Total member stiffness
k_{m1}	[$MN \cdot mm^{-1}$]	First member stiffness

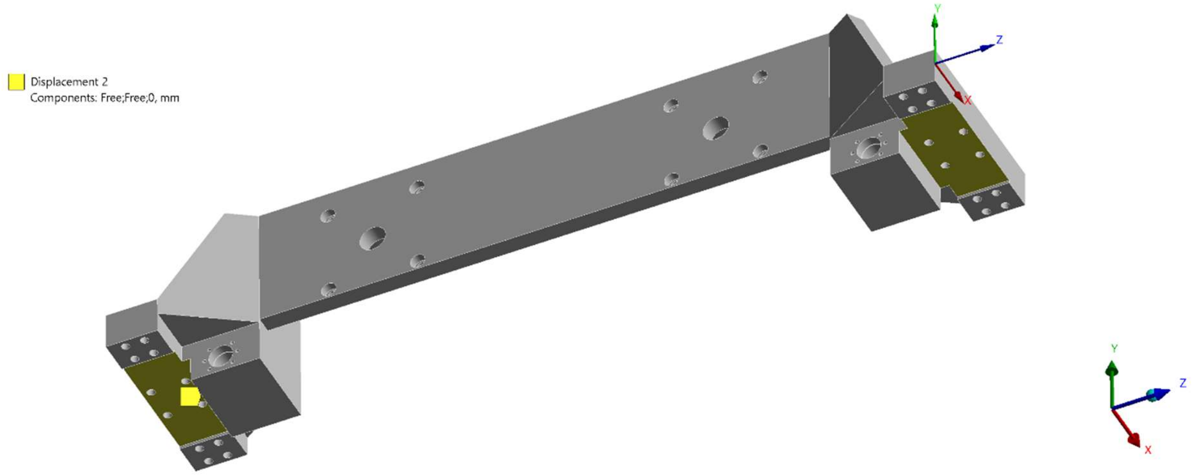
k_{m2}	[MN·mm^{-1}]	Second member stiffness
k_{m3}	[MN·mm^{-1}]	Third member stiffness
L	[mm]	Fastener length
l	[mm]	Grip length
l_d	[mm]	Length of unthreaded portion in grip
l_s	[mm]	Maximal length of the exposed linear shaft
L_T	[mm]	Threaded length
l_t	[mm]	Length of threaded portion in grip
M_{ox}	[MPa]	Static torque in x-axis
M_{oy}	[MPa]	Static torque in y-axis
M_{oymax}	[MPa]	Maximal permissible static torque in y-axis
M_{oz}	[MPa]	Static torque in z-axis
N	[–]	Number of used bolts
n_L	[–]	Load factor
n_p	[–]	Safety factor
n_{p1}	[–]	Safety factor
n_{p2}	[–]	Safety factor
N_t	[–]	Number of threads in a material
P	[N]	External load
p	[mm]	Thread pitch
p_b	[MPa]	Screw Bearing Pressure
p_{bmax}	[MPa]	Maximal permissible Screw Bearing Pressure
P_h	[N]	Pneumatic clamp holding force
p_{sc}	[mm]	Ball screw thread pitch
q	[J·s^{-1}]	Rate of heat flow through an area
r	[mm]	Level arm
$R_{p0,2b}$	[MPa]	Minimum Yield Strength of selected fastener
$R_{p0,2s}$	[MPa]	Minimum Yield Strength of linear shaft
S_p	[MPa]	Minimum Proof Strength of selected fastener
T	[N·m]	Total torque
t_1	[mm]	First cone length
t_2	[mm]	Second material thickness
t_{22}	[mm]	Second cone length

t_3	[mm]	Third cone length
T_c	[N·m]	Necessary torque to overcome friction on the collar face
T_t	[N·m]	Necessary torque to overcome friction in the threads
y_{max}	[mm]	Beam deflection
y_{perm}	[mm]	Permissible beam deflection
α	[°]	Thread angle
α_c	[°]	Half-apex angle of general cone geometry
Θ	[°]	Angle between the level arm and the external load
σ	[MPa]	Bending stress
σ_{HMH}	[MPa]	Equivalent stress according to HMH
σ_i	[MPa]	Preload stress
τ	[MPa]	Shear stress

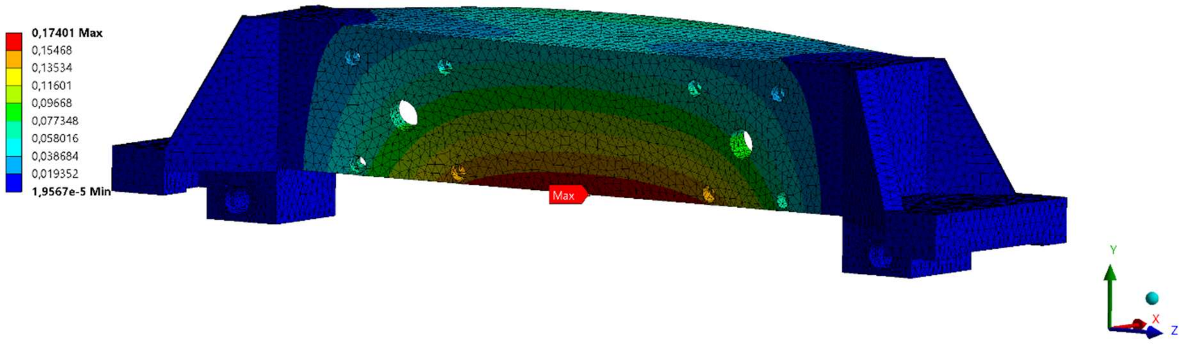
LIST OF APPENDICES



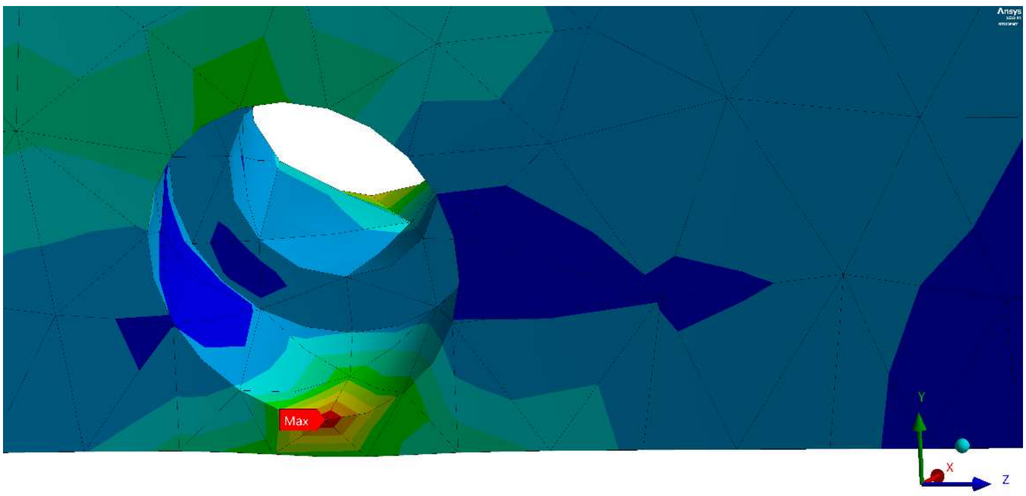
App. 1 Created mesh in static structural analysis (Both approaches)



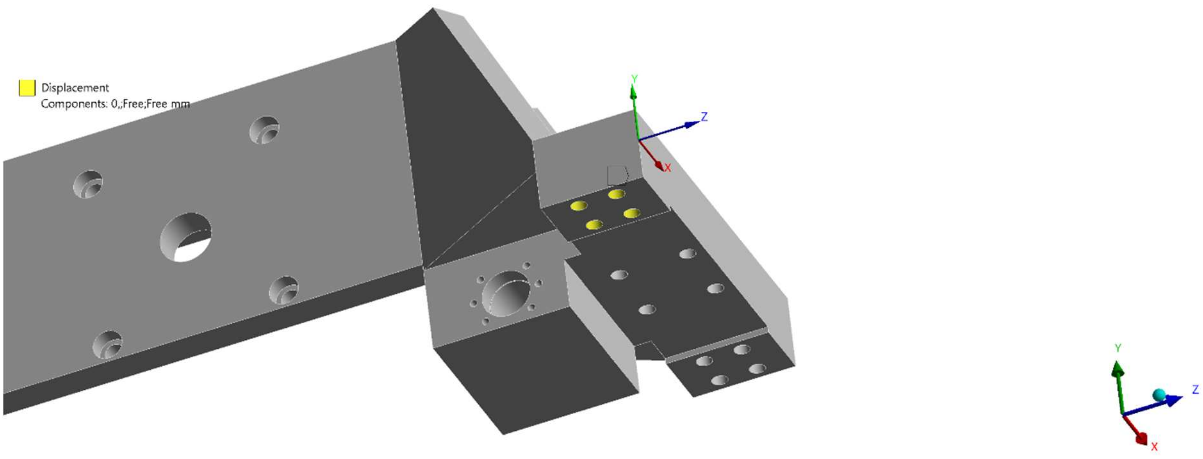
App. 2 Selection of second displacement application faces (First approach)



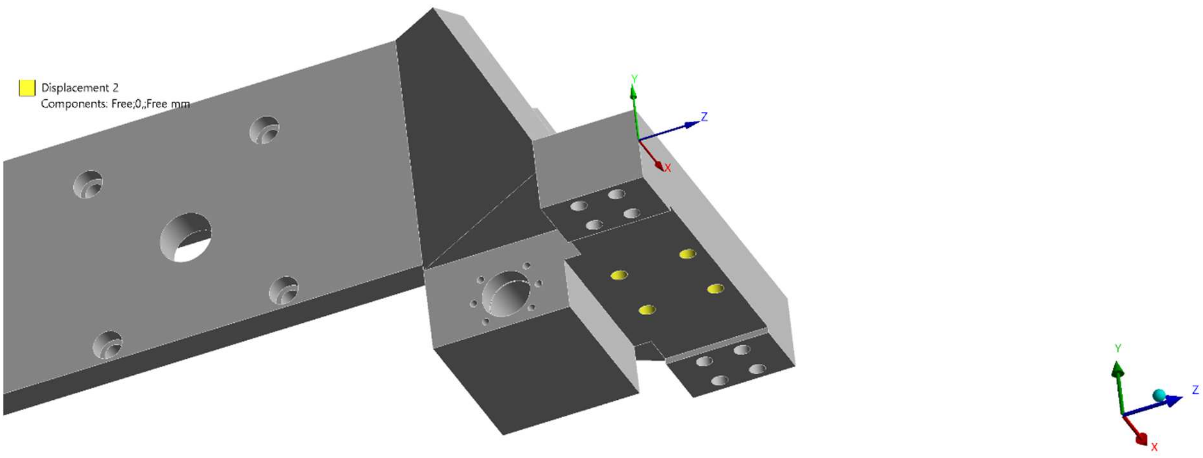
App. 3 Maximal deformation [mm] (First approach)



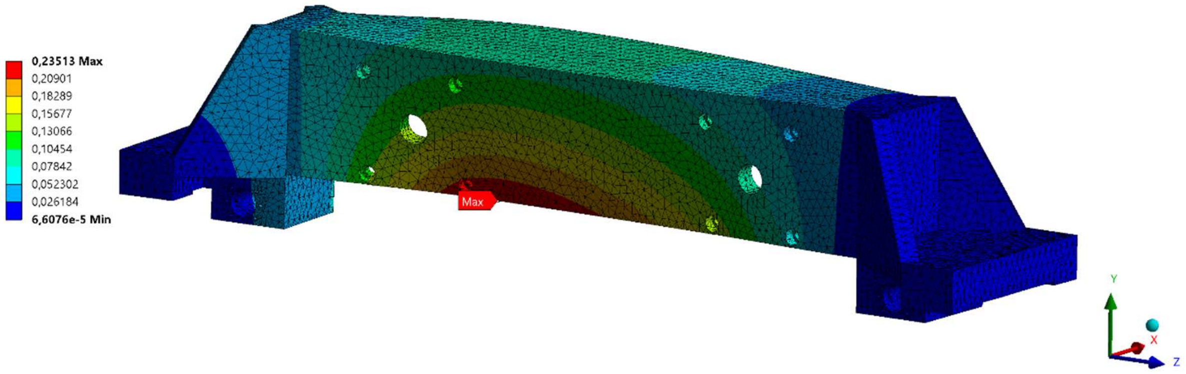
App. 4 Maximal equivalent stress detail 20,933 MPa (First approach)



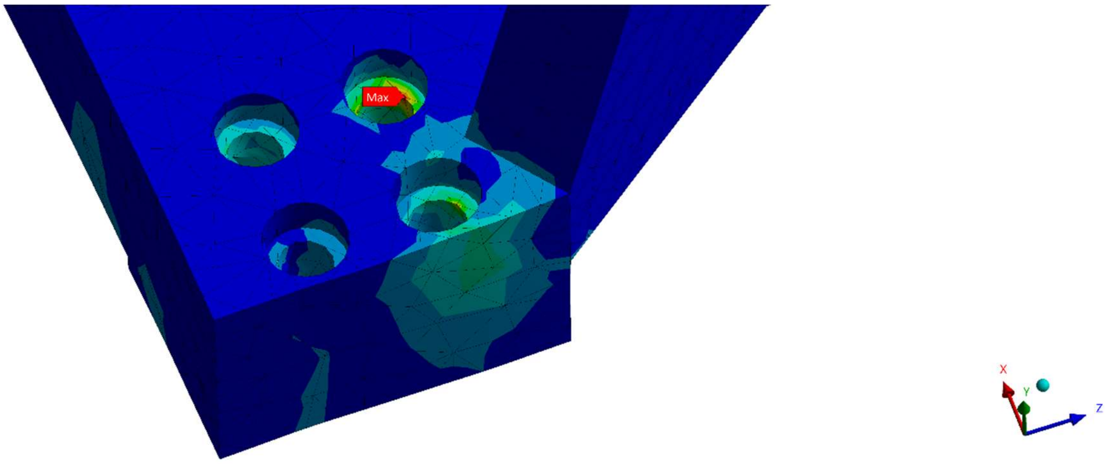
App. 5 Selection of first displacement application faces (Second approach)



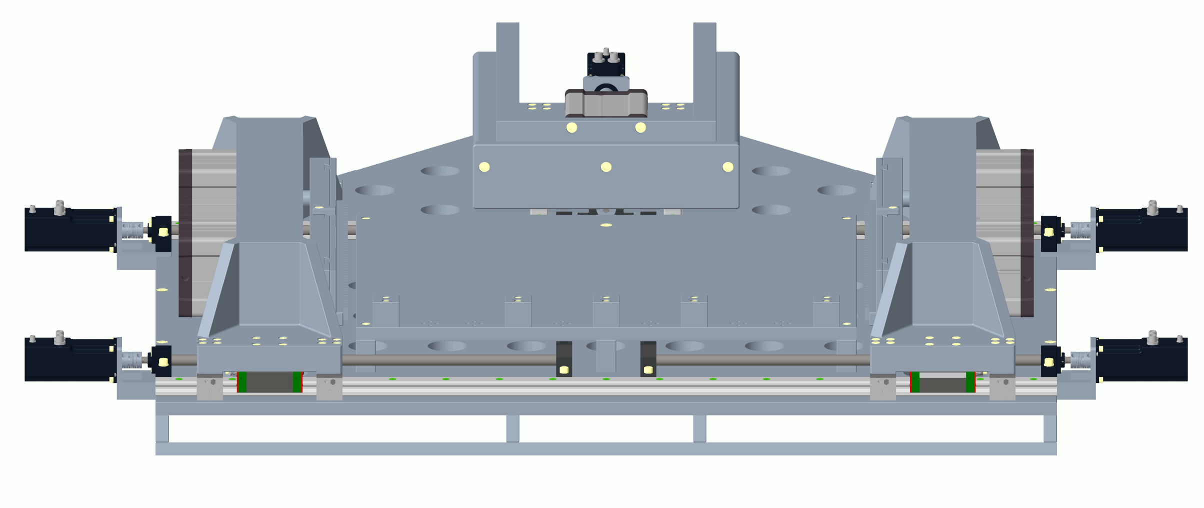
App. 6: Selection of second displacement application faces (Second approach)



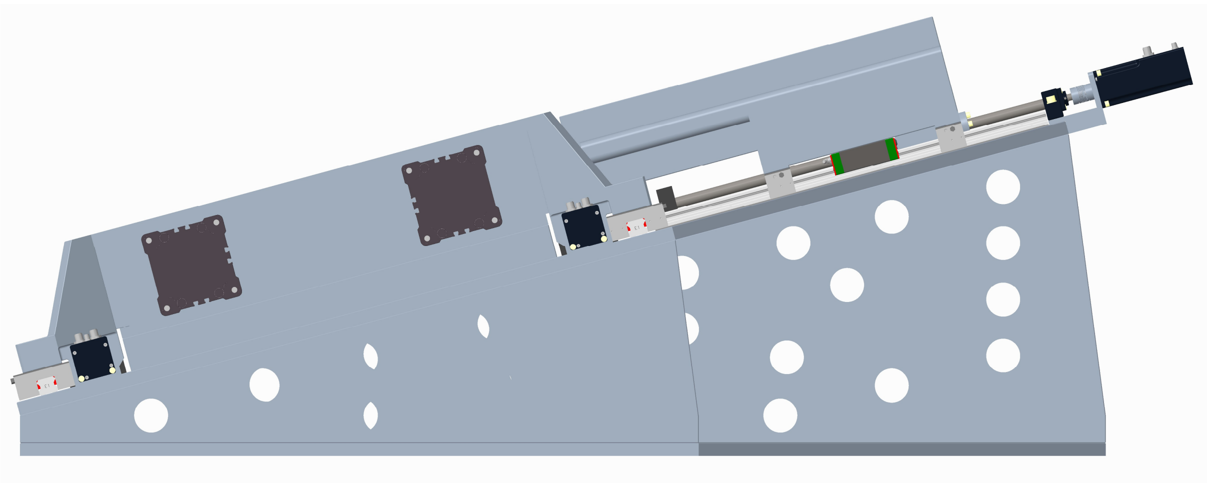
App. 7 Maximal deformation [mm] (Second approach)



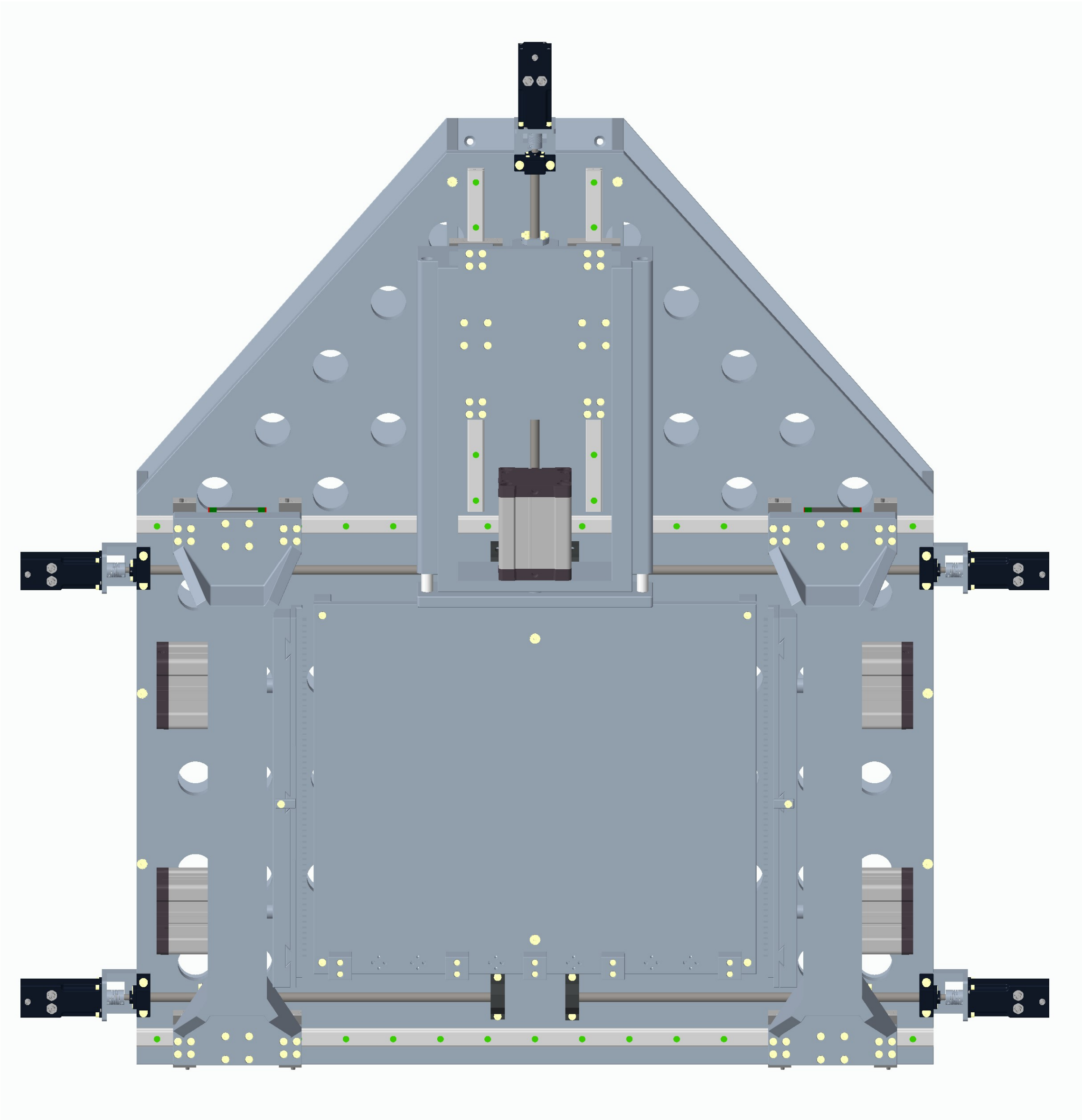
App. 8 Maximal equivalent stress detail 52,747 MPa (Second approach)



App. 9 The final construction design (Front view)



App. 10 The final construction design (Right view)



App. 11 The final construction design (Top view)