CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING
DEPARTMENT OF PROCESS ENGINEERING

DESIGN OF OIL TANK FOR LUBRICATION SYSTEM OF A FORMULA STUDENT CAR

BACHELOR THESIS

AUTHOR:	Barbora Ďurkovičová
THESIS DIRECTOR:	prof. Ing. Tomáš Jirout, Ph.D.

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ZADÁNÍ BAKALÁŘSKÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: **Ďurkovičová** Jméno: **Barbora** Osobní číslo: **475077**

Fakulta/ústav: **Fakulta strojní**

Zadávající katedra/ústav: **Ústav procesní a zpracovatelské techniky**

Studijní program: **Teoretický základ strojního inženýrství**

Studijní obor: **bez oboru**

II. ÚDAJE K BAKALÁŘSKÉ PRÁCI

Název bakalářské práce:

Návrh olejové nádoby pro mazací systém motoru studentské formule

Název bakalářské práce anglicky:

Design of oil tank for lubrication system of a Formula Student car

Pokyny pro vypracování:

Zpracujte návrh olejové nádoby pro mazací systém studentské formule. Při zpracování zadání proveďte následující činnosti:

1. Zpracujte rešerši technického řešení separace plynné fáze v podobě bublinek z kapaliny.
2. Na základě výsledků rešerše a zadaných podmínek pro aplikace na studentskou formuli zpracujte variantní řešení separátoru.
3. Vytvořte zjednodušený model vybrané koncepce separátoru.
4. Ověřte navržené technické řešení pomocí CFD simulací nebo základními experimenty s modelem separátoru.

Seznam doporučené literatury:

Dle doporučení vedoucího práce a vlastní rešerše.

Jméno a pracoviště vedoucí(ho) bakalářské práce:

prof. Ing. Tomáš Jirout, Ph.D., ústav procesní a zpracovatelské techniky FS

Jméno a pracoviště druhé(ho) vedoucí(ho) nebo konzultanta(ky) bakalářské práce:

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prof. Ing. Tomáš Jirout, Ph.D. podpis vedoucí(ho) práce	prof. Ing. Tomáš Jirout, Ph.D. podpis vedoucí(ho) ústavu/katedry	prof. Ing. Michael Valášek, DrSc. podpis děkana(ky)

III. PŘEVZETÍ ZADÁNÍ

Studentka bere na vědomí, že je povinna vypracovat bakalářskou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v bakalářské práci.

Datum převzetí zadání	Podpis studentky

I confirm that the bachelor's work was disposed by myself and independently, under leading of my thesis supervisor. I stated all sources of the documents and literature.

In Prague ………………   …………………

Name and Surname

Acknowledgment

I would like to thank my thesis director, prof. Ing. Tomáš Jirout, Ph.D., for his leading and professional advices, and doc. Ing. Jan Skočilas, Ph.D. for consultations on numerical simulations.

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Annotation sheet

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Abstract

The purpose of this thesis is to design oil tank for storage and deaeration of oil for dry sump lubrication system of a Formula Student car. Air bubbles in oil that lubricates parts of engine decrease effectiveness of lubrication, hence must be from oil separated. Research on problem covers possible separation methods including gravitational and centrifugal and also gives examples on commonly manufactured oil tanks and materials they are made from. Calculations of gravitational separation show that another method is necessary to use. Comparison of cyclone separator and in-line separator results in cyclone separator design in three variations. Geometry of the first modification, separator with smooth wall, is used for CFD simulation of laminar and turbulent flow of oil. Results of the turbulent flow simulation are input values for investigation of the centrifugal separation of air bubbles. Results of both calculations prove that designed separator with smooth wall is suitable for separation of air bubbles with diameters higher than 0,25 mm. Conclusion gives suggestions on increase of the separation effectiveness as well as points out possibilities for future development and testing of separators.

Abstrakt

Cílem práce je navrhnout olejovou nádobu pro uskladnění a odvzdušnění oleje pro systém suché vany vozu studentské formuli. Bubliny vzduchu v oleji, který maže součásti motoru, snižují účinnost mazání, a proto musí být z oleje odseparovány. Rešerše problému zahrnuje možné metody separace včetně gravitační a odstředivé a ukazuje příklady běžně dostupných olejových nádob a materiálů, ze kterých jsou vyráběny. Výsledky výpočtů gravitačního odlučování ukazují, že je nutné použít další metodu separace. Z porovnání cyklonového a in-line odlučovače je vybrán cyklonový odlučovač, který je navržen ve třech variantních provedeních. Geometrie prvního provedení, separátoru s hladkou stěnou, je použita pro CFD simulaci laminárního a turbulentního proudění oleje. Výsledky turbulentního proudění jsou východiskem pro inspekci odstředivého odlučování bublin v separátoru. Výsledné hodnoty obou simulací prokazují, že cyklonový separátor s hladkou stěnou je vhodný pro odlučování bublin o průměru vyšším než 0,25 mm. V závěru jsou rozebrány možná řešení pro zvýšení účinnosti separace, jako i možnosti dalšího vývoje a testování separátorů.

Content

Introduction

The purpose of this thesis is to design oil tank for storage and deaeration of oil for dry sump lubrication system of a Formula Student car. Dry sump lubrication system is widely used in race cars engines because of several advantages upon wet sump lubrication system. One of these advantages is storage of oil in separate oil tank with oil deaeration. Deaeration of oil is important because air bubbles contained in oil influence its correct function in lubricating the engine parts.

In the beginning, the thesis introduces brief description of Formula Student competition. Then it moves to explanation of dry sump lubrication system including oil tank designed for previous car and reasons for its new design. The inevitable part is problem research where are shown various examples of designed oil tanks and materials they are usually made from. The second part of the research deals with separation methods and examples of separators. In the next portion are described calculations of gravitational separation and decision is made about use of another separation method. After creation of oil tank model, evaluation of effectiveness of centrifugal deaeration is carried out by calculations based on CFD simulations. The last part of the thesis shows design of testing oil tank and analyse possible manufacturing methods.

1. Formula Student competition overview

Formula Student is annually held competition in which teams formed of university students compete with small formula style race cars, designed, and manufactured by themselves. Each team must build every year new car with significant changes to its predecessor. Every car entering the competition must comply with the rules of the competition. The competition is split into three classes: Internal combustion engine vehicles, Electric vehicles, and Driverless vehicles. Teams in each class compete in the series of dynamic and static events and for each discipline are awarded points. The one with the highest number of overall points wins the competition. Combustion vehicle team of Czech Technical University in Prague is CTU CarTech Formula Student team since its first built car in 2008. This year students work on the 13. car with the title FS.13. [1]

2. Problem overview

2.1. Dry sump lubrication system

Many race car engines use dry sump lubrication system instead of the wet sump lubrication system used in normal road vehicles. The use of dry sump lubrication system in race cars has few advantages: it allows to lower the centre of gravity of the car, hence improves its handling and weight distribution, eliminates sloshing of oil in the sump under high gravitational forces that causes insufficient suction of oil to engine and allows separation of air bubbles from oil. Deaeration of oil is important because air bubbles contained in oil affect correct functionality of lubricant between piston and engine cylinder. Air contained in oil results from following:

a) suction of oil-air mixture from engine by the scavenge pump,
b) dissolved air (cavitation- at certain conditions, as decrease of static pressure or increase of oil temperature, causes reduction of air solubility in oil that induces formation of air bubbles),
c) suction of air from outside because of tightness imperfections in sealings. [2]

The difference in assembly of the wet sump system and dry sump system is replacement of the wet sump under the engine by much thinner dry sump. Oil from engine is sucked by the scavenge pump, located in the dry sump, into the oil filter and oil cooling unit and then to separate oil tank. In this oil reservoir is oil deaerated. As mentioned above oil deaeration is critical because it affects effectivity of lubrication process in the engine. After deaeration is oil in the reservoir stored until it flows back to engine through the high-pressure pump. In the Figure 1 below is shown dry sump lubrication system of FS.12 car with description of its parts.

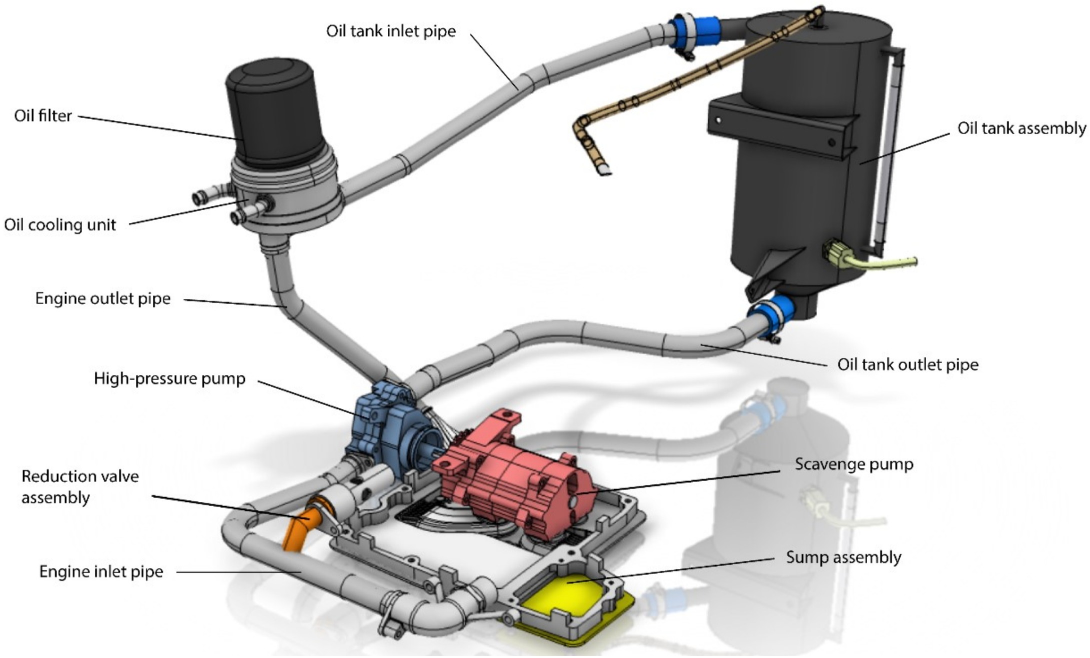

Figure 1: Dry sump lubrication system of FS.12 car

2.2. FS.12 oil tank

Oil tank designed for FS.12 car was cyclone separator with tangential inlet at the top of the tank. Figures 2 and 3 shows its structure. After the inlet was placed helix to direct stream of oil for more effective separation of air bubbles. At the centreline of the separator was placed vent tube for separated air. Oil outlet was located horizontally at the bottom of the tank. Bottom part comprised of conic section and cylinder with smaller diameter than main cylinder to ensure sufficient volume of oil for outlet at any time. At the bottom was also located partition that prevents oil from sloshing. The volume of the tank was 2,6l. The volume of oil in the tank was 1,86l. Oil tank was mounted to frame by two M5 bolts on upper holder and one M5 bolt on lower holder. It was made from aluminium, EN AW 6063, and welded from bended sheets of 1 mm thickness, laser cut parts and tubes of different diameters and 1 mm wall thickness.

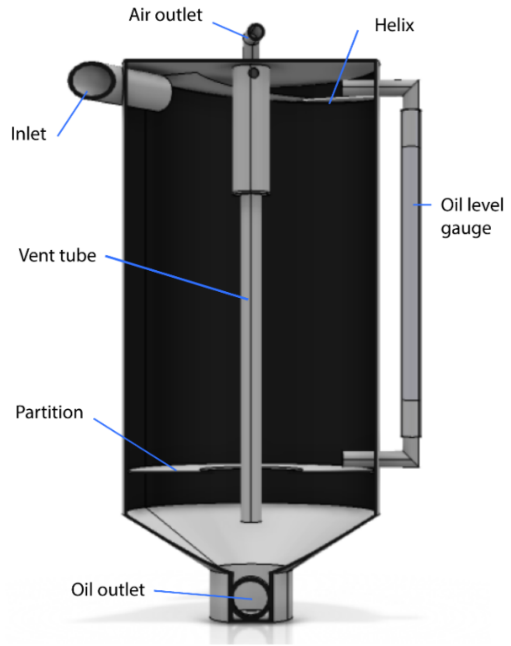

Figure 2: Inner structure of FS.12 oil tank

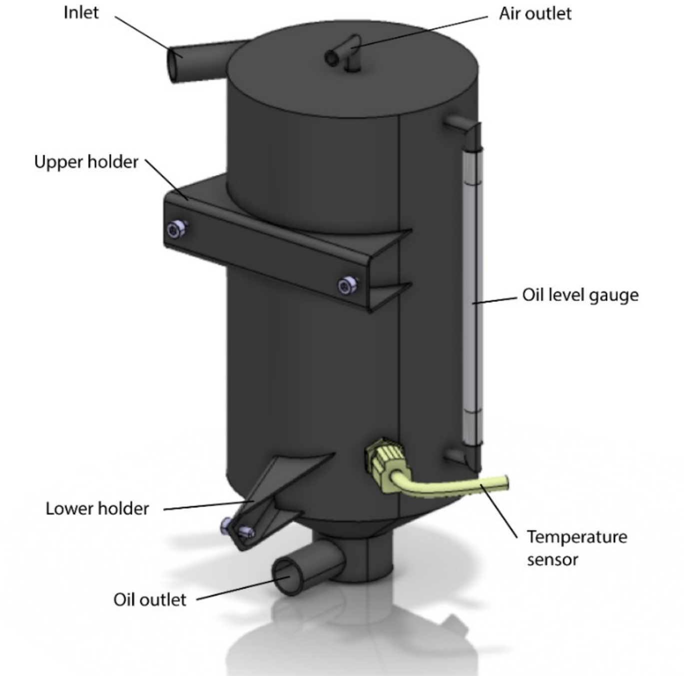

Figure 3: Outer structure of FS.12 oil tank

Reasons for new oil tank design:

1) Relocate tank to better position in order to have all engine components inside the frame space. This relocation has positive impact on the moment of inertia and easifies design of aerodynamic devices that are no more limited by position of the tank
2) Optimise design of the oil- air separator regards the new tank position.
3) Reduce mass of the tank and separator. Another mass reduction is achieved by moving the tank closer to the engine hence allows shortening the inlet and outlet leading tubes.

3. Research on topic

3.1. Oil tank

Before designing oil tank was necessary to do some research on the topic. In this part of the research are included examples of separate oil tanks with build-in oil-air separators, separators implemented into the scavenge pump or oil tanks made from less usual materials as thermoplastic. All of the following solutions are designed for the use in dry sump lubrication system.

As the first design is described dry sump oil tank assembly for a vehicle according to patent [3]. In the Figure 4 is shown assembly of the dry sump lubrication oil tank and engine. Oil from engine is directed to the oil tank by hose 16.

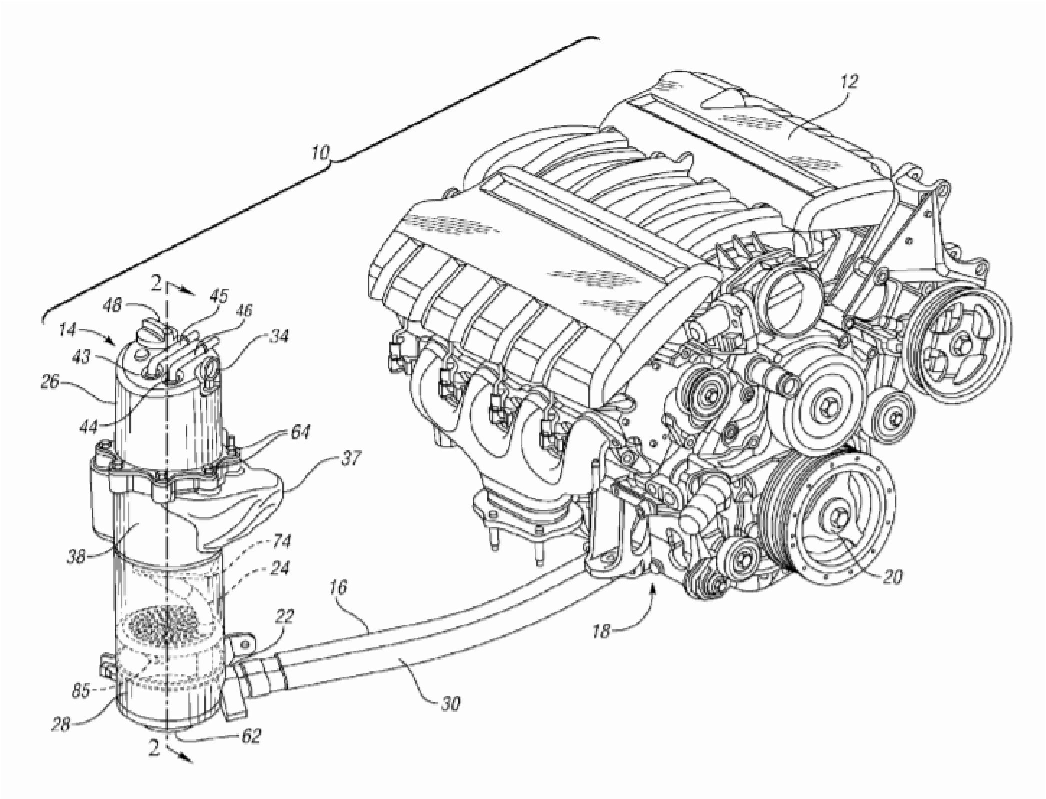

Figure 4: Engine and oil tank assembly [3]

As figured in the picture on the right, oil from oil inlet hose 16 flows through the connecting hose 24 and enters air separator 26. In the air separator is located internal baffling 50 which consists of vertical guidance section 51, opening of the upper section 52 and upper section 53 of the separator. Shape of the baffling section spins oil entered from the connecting hose down through the separator and causes separation of air bubbles contained in oil. Deaerated oil then flows downwards to oil outlet 58 located at the bottom of the oil tank and returns to engine through the return hose 30.

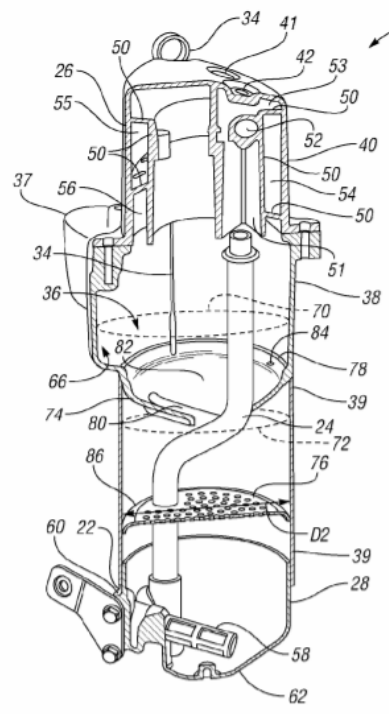

FIG. 2

Figure 5: Oil tank assembly [3]

In the Figure 6 is shown another oil tank assembly. The oil tank consists of upper compartment 13 with air separator and bottom compartment 14 where oil is stored. Aerated oil from engine flows into the deaerator through tangentially positioned inlet tube 17. In the centrifugal separator 16 oil rotates on the interior surface of the separator. Air with lower density accumulates in the centre of separator, escapes through the opening 16a to the top compartment 13 and then continues to air outlet 15. Deaerated oil is stored in the bottom compartment until it is sucked back to engine through oil outlet 19. [4]

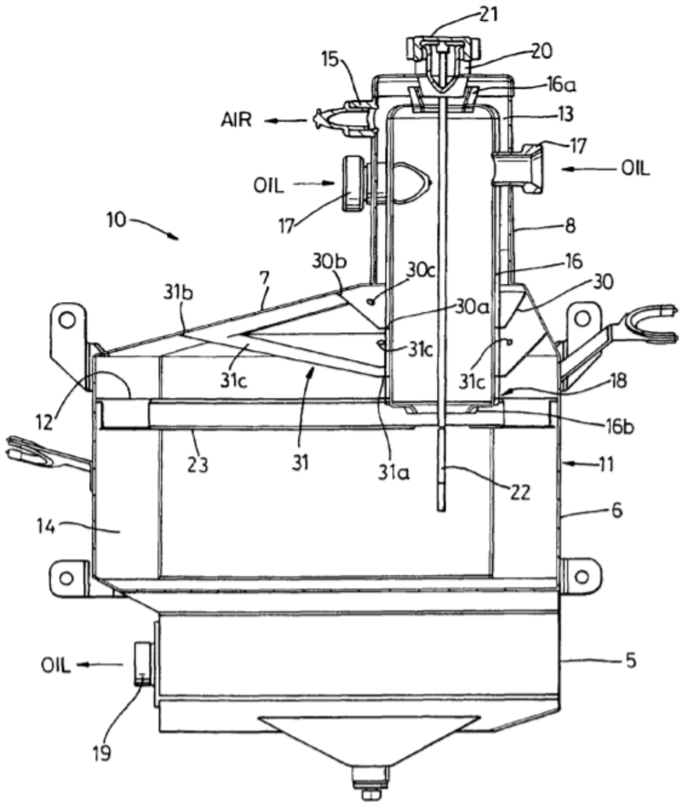

Figure 6: Aston Martin Lagonda oil tank assembly [4]

Scavenge pump designed by the manufacturer Dailey Engineering is example of possibility of locating oil- air separator in other parts of dry sump lubrication system than oil tank. Designer's decision was to integrate air separator into the scavenge pump which sucks oil from the dry sump located under the engine. The separator is located on the right side of the scavenge pump shown in the Figure 7. Aerated oil enters centrifugal separator. As described in previous examples, centrifugal forces force oil to the rotational move on the wall where heavier oil keeps rotating and goes out of the separator by oil outlet, lighter air accumulates in the center and flows out by air outlet. [5]

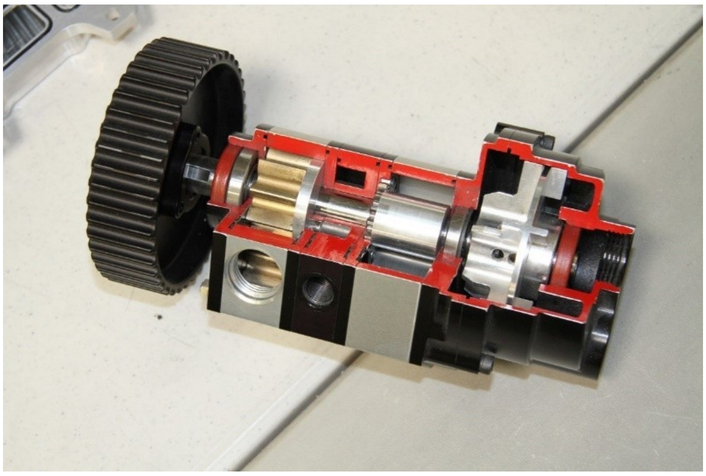

Figure 7: Scavenge pump by Dailey Engineering [6]

Materials of oil tanks:

Most oil tanks used for dry sump lubrication systems are made of metal sheets, shaped or bended into the desired shape and welded together. There is a tendency to design high thin tanks with cylindrical shape and built-in centrifugal deaerator. In the Figures 8 and 9 are examples of such oil tanks made of aluminium with integrated air separator. Aluminium is used for its convenient ratio between weight and stiffness. It enables to fabricate tank with thinner walls, hence lighter but keeps it stiff enough to carry all load. Moreover, its thermal resistance is essential in this kind of application.

Figure 8: Dry Sump Solutions oil tank [8]

Figure 9: Pro Alloy Motorsport oil tank [7]

Apart from aluminium oil tanks, another material of which oil reservoir can be made is plastic. Company Hummel- Formen in Germany developed, according to [9], first thermoplastic oil tank for dry sump system used in Mercedes- AMG M178 V8 engine. Oil tank is made from BASF polyamide 66 with 35% glass fibre reinforcement and prevents tank from oil and thermal aging. The use of plastic reduces weight of the tank by 59% in comparison to the steel or aluminium welded and its thermal resistance is about 180°C. The tank comprises of many components including integrated air separator that are connected by vibration welding and snap- in mechanisms.

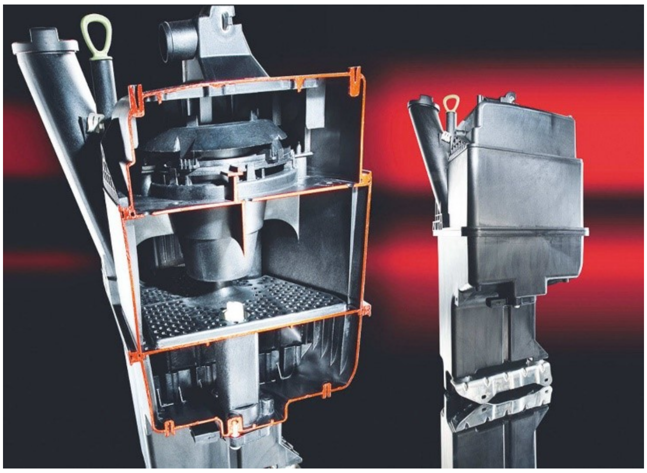

Figure 10: Mercedes-AMG GT thermoplastic oil tank [9]

3.2. Separation methods research

In the previous examples was shown that manufacturers use mostly centrifugal separators for oil-air separation. In the next part of the research, I decided to describe possible separation options for Formula Student car oil tank design and based on this research make decision which type of separation method will be used for this application.

1) Gravitational separation

Gravitational separation is based on different gravitational forces acting on separated particles in dispersion. As known from Archimedes law, if density of particles is higher than fluid density, particles flow to the bottom of the separator with sedimentation velocity. If density of particles is lower than density of fluid, particles flow with rising velocity upwards to the free surface of fluid.

a) Continuous sedimentation tank

Picture of such separator is shown in the Figure 11.

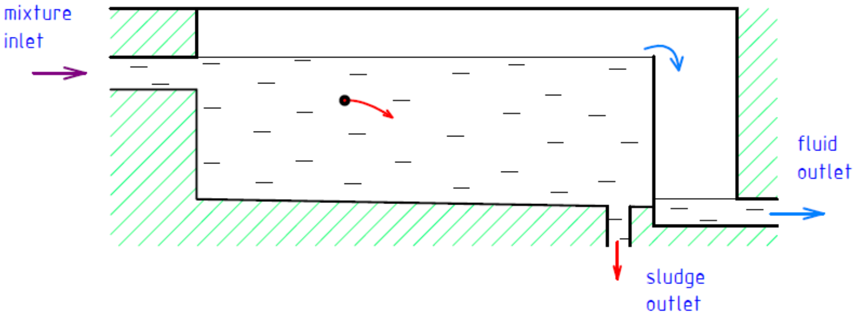

Figure 11: Continuous sedimentation tank

On the left side is inlet of dispersion that continuously flows to the sedimentation tank where heavier particles sediment at the bottom and lighter flow to the free surface of fluid. Particles must be separated before fluid comes to the outlet on the right side of the sedimentation tank.

b) Lamella separator

Lamella separator, as title says, consists of obliquely assembled lamellas. As dispersion flow through these lamellas, heavier particles settle on their walls and slowly slide down to sludge outlet.

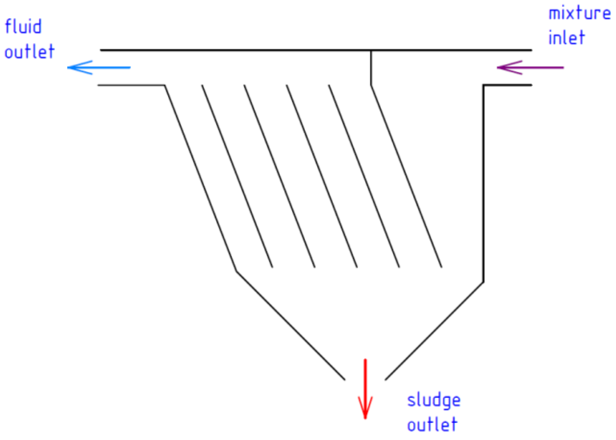

Figure 12: Lamella separator

2) Centrifugal separation

The separation principle of the centrifugal separators are different centrifugal forces acting on separated phases. In the separator that is usually of cylindrical or conic shape is dispersion rotated. Heavier phase rotates on the wall and flows down to outlet. Lighter phase accumulates in the centre and flows upwards to the second outlet on the top of the centrifugal separator.

1. Cyclone separator

Principle of function is as described above. Inlet is placed tangentially and on the top of the main cylinder. Heavier particles are drained through outlet at the bottom, lighter phase flows out through the outlet positioned on centreline and on the top of the separator.

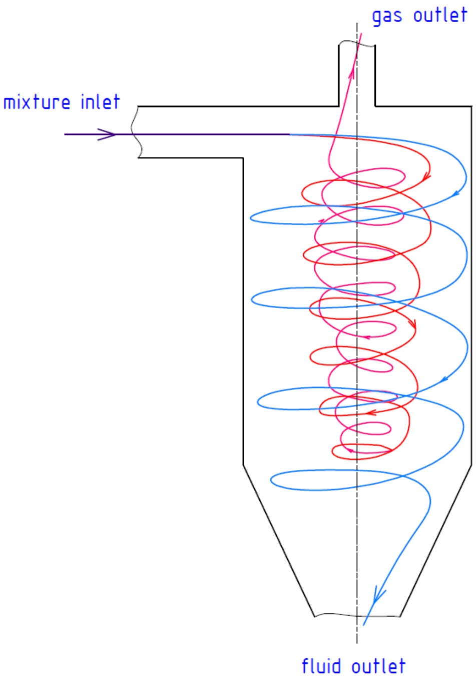

Figure 13: Cyclone separator

2. In-line separator

Working principle of an in-line separator is similar to the cyclone separator but there are differences in their construction. In- line separator has inlet located at centreline and spinning of the mixture is caused by swirling component placed behind the inlet. Heavier phase rotates on inner surface of separator and is led out through outlet placed at the bottom. Lighter phase goes out through the outlet at the centreline of separator.

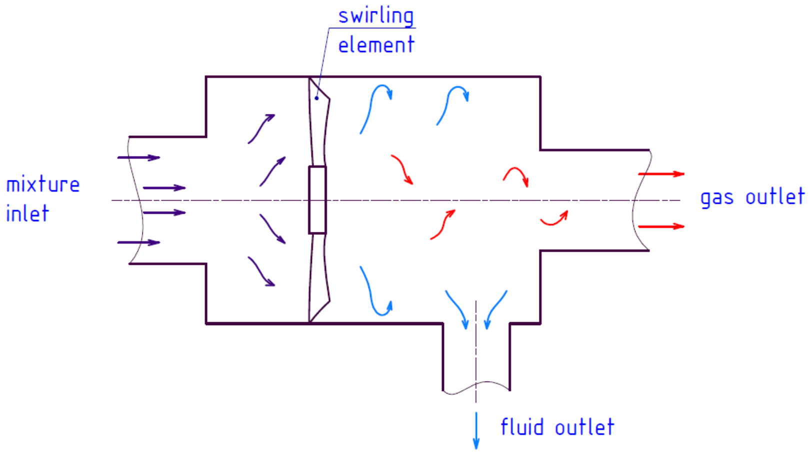

Figure 14: In-line separator

4. Choice of separation method

4.1. Gravitational separation

Firstly, is necessary to calculate whether gravitational separation in oil tank is sufficient for air bubbles separation. It means whether bubbles of specified diameters are able to reach free surface of oil in shorter period than is residence time of oil in the tank.

Firs of all parameters of oil and air defined:

General characteristics:

Table 1: General characteristics

Temperature	t	100	[°C]
Gravitational acceleration	g	9,81	[m/s^2]

Parameters of oil:

Table 2: Characteristics of oil [10]

Oil		Shell Advance Ultra 4T 10W-40	
Kinematic viscosity	υ (100°C)	14,2	[mm^2/s]
Density	ρ_o (100°C)	820	[kg/m^3]

Parameters of air:

Table 3: Characteristics of air

Air					
Kinematic viscosity		υ_a (100°C)		23,06	[mm^2/s]
Pressure	p	[bar]	Density	ρ_A (100°C)	[kg/m^3]
	1			0,93359	
	1,5			1,40038	
	2			1,86717	
	2,5			2,33396	
	3			2,80076	
	3,5			3,26755	

Range of the pressure values in the Table 3 are gained from data measured by engine oil pressure sensor during Autocross event, FS Italy 2019.

Selected radiuses of air bubbles:

Table 4: Selected bubble radiuses

Bubble radius r	[m]	0,00025	0,0005	0,0008	0,001	0,0013	0,0015	0,0018

Then are calculated rising velocities of air bubbles for each bubble diameter and air density according to equilibrium of the acting forces:

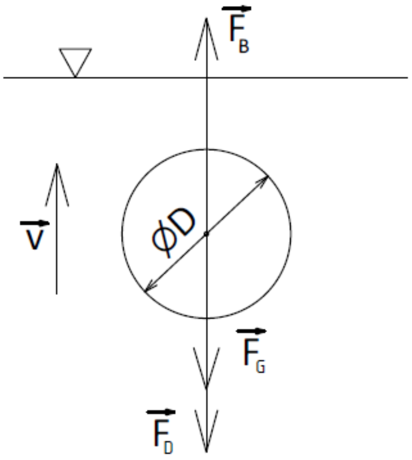

Figure 15: Forces acting on a bubble

Equilibrium:

$$\sum F = 0 \tag{1}$$

$$F_B - F_G - F_D = 0 \tag{2}$$

where F_B is buoyancy force, F_G is gravitational force and F_D is drag force. These forces are defined as:

$$F_B = \rho_o \cdot V_o \cdot g \tag{3}$$

where V_o is volume of oil displaced by the air bubble,

$$F_G = m_A \cdot g = \rho_A \cdot V_A \cdot g \tag{4}$$

where m_A is mass of air bubble and V_A its volume,

$$F_D = 6\pi \cdot \eta \cdot r \cdot v \tag{5}$$

η is dynamic viscosity of oil, r is defined as radius of bubble and v is its rising velocity.

After substituting forces for their expressions

$$\rho_o \cdot V_o \cdot g - \rho_A \cdot V_A \cdot g - 6\pi \cdot \eta \cdot r \cdot v = 0 \tag{6}$$

and stating that the volume of air bubble equals volume of displaced oil

$$V_A = V_o \tag{7}$$

is rising velocity of the air bubble expressed:

$$v = \frac{\rho_o \cdot V_A \cdot g - \rho_A \cdot V_A \cdot g}{6\pi \cdot \eta \cdot r} \tag{8}$$

Calculated rising velocities:

Table 5: Rising velocities of air bubbles

	Bubble radius r [m]						
Velocity [m/s]	0,00025	0,0005	0,0008	0,001	0,0013	0,0015	0,0018
0,93359	0,0096	0,0383	0,0981	0,1533	0,2396	0,3450	0,4968
1,40038	0,0096	0,0383	0,0981	0,1533	0,2395	0,3448	0,4966
1,86717	0,0096	0,0383	0,0980	0,1532	0,2393	0,3446	0,4963
2,33396	0,0096	0,0383	0,0980	0,1531	0,2392	0,3444	0,4960
2,80076	0,0096	0,0382	0,0979	0,1530	0,2391	0,3442	0,4957
3,26755	0,0096	0,0382	0,0979	0,1529	0,2389	0,3440	0,4954
Air density ρ_A (100°C) [kg/m^3]							

Reynolds numbers are calculated according to:

$$Re = \frac{v \cdot d}{\upsilon} \tag{9}$$

Table 6: Reynolds numbers of air bubbles

	Bubble radius r [m]						
Re [-]	0,00025	0,0005	0,0008	0,001	0,0013	0,0015	0,0018
0,93359	0,208	1,662	6,809	13,300	25,976	44,887	77,564
1,40038	0,208	1,662	6,806	13,292	25,961	44,861	77,520
1,86717	0,208	1,661	6,802	13,285	25,947	44,836	77,476
2,33396	0,207	1,660	6,798	13,277	25,932	44,810	77,432
2,80076	0,207	1,659	6,794	13,269	25,917	44,784	77,387
3,26755	0,207	1,658	6,790	13,262	25,902	44,759	77,343
Air density ρ_A (100°C) [kg/m^3]							

For Re>9 must be the rising velocities recalculated according to equation:

$$v = \sqrt{\frac{4}{3} \cdot \frac{D \cdot (\rho_A - \rho_o) \cdot g}{C_D \cdot \rho_o}} \tag{10}$$

where for Re>9 applies coefficient

$$C_D = \frac{8}{3}$$

Recalculated rising velocities of air bubbles:

Table 7: Recalculated rising velocities for Re>9

Re>9	Bubble radius r [m]			
Velocity [m/s]	0,001	0,0013	0,0015	0,0018
0,93359	0,0990	0,1129	0,1212	0,1328
1,40038	0,0990	0,1128	0,1212	0,1328
1,86717	0,0989	0,1128	0,1212	0,1327
2,33396	0,0989	0,1128	0,1211	0,1327
2,80076	0,0989	0,1127	0,1211	0,1327
3,26755	0,0988	0,1127	0,1211	0,1326
Air density ρ_A (100°C) [kg/m^3]				

Recalculated Reynolds numbers of air bubbles:

Table 8: Recalculated Reynolds numbers

	Bubble radius r [m]			
Re [-]	0,001	0,0013	0,0015	0,0018
0,93359	13,942	20,665	25,613	33,670
1,40038	13,938	20,660	25,606	33,660
1,86717	13,934	20,654	25,599	33,650
2,33396	13,930	20,648	25,591	33,641
2,80076	13,926	20,642	25,584	33,631
3,26755	13,922	20,636	25,577	33,622
Air density ρ_A (100°C) [kg/m^3]				

Because of small differences in rising velocities of bubbles are taken their average values for each bubble diameter.

Table 9: Average rising velocities

Bubble radius r [m]	0,00025	0,0005	0,0008	0,001	0,0013	0,0015	0,0018
Average velocity [m/s]	0,0096	0,0383	0,0980	0,0989	0,1128	0,1211	0,1327

For each velocity is calculated rising time of air bubble from the bottom of the tank to the free oil surface according to equation:

$$s = v \cdot t_b \tag{11}$$

where s is distance gone by bubble from bottom to free surface of oil, v is rising velocity of air bubble and t_b is calculated rising time of a bubble. After expressing time from equation (11)

$$t_b = \frac{s}{v} \tag{12}$$

and substituting for $s = 188\ mm$ and v average velocity of each bubble diameter, is rising time calculated:

Table 10: Rising time of air bubbles in gravitational field

Bubble radius r [m]	0,00025	0,0005	0,0008	0,001	0,0013	0,0015	0,0018
Rising time of bubble t_b [s]	19,644	4,911	1,918	1,901	1,667	1,552	1,417

Period during which bubble rises to the fluid level is compared to the residence time of oil in the tank. Residence time is calculated from volume of oil in the tank and volumetric flow rate through the pump that circulates the oil to the engine, high-pressure pump, for each engine rpms.

For the calculation of residence time of oil in the tank is used equation:

$$\dot{V}_{hp} = \frac{V}{t_o} \tag{13}$$

After moving t_o on the left side and dividing with volumetric flow rate $\dot{V}_{hp}$ is obtained equation in the form:

$$t_o = \frac{V}{\dot{V}_{hp}} \tag{14}$$

where t_o is residence time of oil in the oil tank calculated for every engine rpm, $\dot{V}_{hp}$ is volumetric flow rate of oil in the high-pressure pump at defined engine revolutions and V is volume of oil in the tank.

Residence time of oil in the oil tank calculated from equation (14):

Table 11: Residence time of oil in the tank

Engine rpm n_m	Volumetric flow rate- HP pump $\dot{V}_{hp}$	Volume of oil V	Residence time t_o
[1/min]	[l/min]	[l]	[s]
500	1,528	1,867	73,296
1000	3,056		36,648
1500	4,584		24,432
2000	6,112		18,324
2500	7,640		14,659
3000	9,168		12,216
3500	10,696		10,471
4000	12,224		9,162
4500	13,752		8,144
5000	15,280		7,330
5500	16,808		6,663
6000	18,337		6,108
6500	19,865		5,638
7000	21,393		5,235
7500	22,921		4,886
8000	24,449		4,581
8500	25,977		4,312
9000	27,505		4,072
9500	29,033		3,858
10000	30,561		3,665
10500	32,089		3,490
11000	33,617		3,332
11500	35,145		3,187
12000	36,673		3,054
12500	38,201		2,932
13000	39,729		2,819

Comparison proves that bubbles with the smallest chosen radius of 0,25 mm do not have time enough to reach the free surface of oil for engine revolutions higher than 2000 1/min. Bubbles with the second smallest observed radius of 0,5 mm do not reach free surface of oil for revolutions above 7000 1/min. Bubbles with radius greater than 0,5 mm are separated from oil by reaching the free surface at the whole range of engine rpm. This comparison shows that another separation method apart from gravitational is necessary to use to separate air bubbles with radius smaller than 0,5 mm (or diameter 1 mm).

4.2. Centrifugal separator selection

Another possible separation method as described in the chapter 3.2 is centrifugal separation. In this chapter were also described two separator configurations using centrifugal principle, cyclone separator and in-line separator. Below are analysed both options with list of their advantages and disadvantages. These are compared and in the end are explained reasons of choice of the selected separator type.

In decision process were firstly defined requirements on separator:

1) position of inlet and outlets
2) weight
3) effectivity of separation, especially at high gravitational forces (acceleration, braking, turning)
4) manufacturing

Comparison of the cyclone separator and in- line separator:

Table 12: Comparison of cyclone and in-line separator

	Cyclone separator	In- line separator
Inlet	Tangential at top	On axis of the separator
Outlet- fluid	At the bottom	At the bottom
Outlet- gas	At the top on axis	On axis of the separator
Separation method	Centrifugal	Centrifugal
Trajectory	Spiral move along the cylindrical wall	Spiral move along the cylindrical wall
Positioning	can be integrated in oil tank or separately on tank inlet pipe or outlet pipe	separately from oil tank, before inlet or outlet of the tank
Weight	addition of directing components as helix increases weight of separator	heavier than cyclone separator because of swirling component
Effectivity	- gravitational forces have no influence on effectivity - may be affected by directing components	- may be affected by gravitational forces - influenced by the shape of swirling component- more complicated design
manufacturing	welded metal sheets, 3D printed (plastic or aluminium)	welded metal sheets, 3D printed (plastic or aluminium)

As results from comparison both cyclone and in- line separators have same principle of function that is separation of two phases based on different centrifugal forces acting on these phases. Differences in construction are position of inlet and outlets. The main advantages of cyclone separator are its integration into oil tank and g- forces do not have influence on correct function of the separator. On the other hand, despite of variability of possible designs, in-line separator has more complicated design of the swirling element. Moreover, its functionality may be reduced when car is turning. Based on the previous research of commonly used oil tanks, separator types and their comparison, I have decided to design cyclone separator positioned at inlet of the oil reservoir.

5. Model

5.1. Separator design

For oil deaeration was chosen cyclone separator as additive separation method. In the next steps is described its design process.

Firstly, are defined requirements on cyclone deaerator design:

1) inlet positioned tangentially at the top of the main cylinder
2) oil outlet- main cylinder of the separator should be open at the bottom. No specified diameter or shape is needed, oil from separator (that is located at the top of the tank) flows directly to the oil tank
3) air vent tube- position at the top of the separator, on axis of the main cylinder
4) the higher diameter of separator the higher effectivity of air bubble separation

Regards the criteria listed above were designed three modifications of deaerator:

I. Deaerator with smooth wall

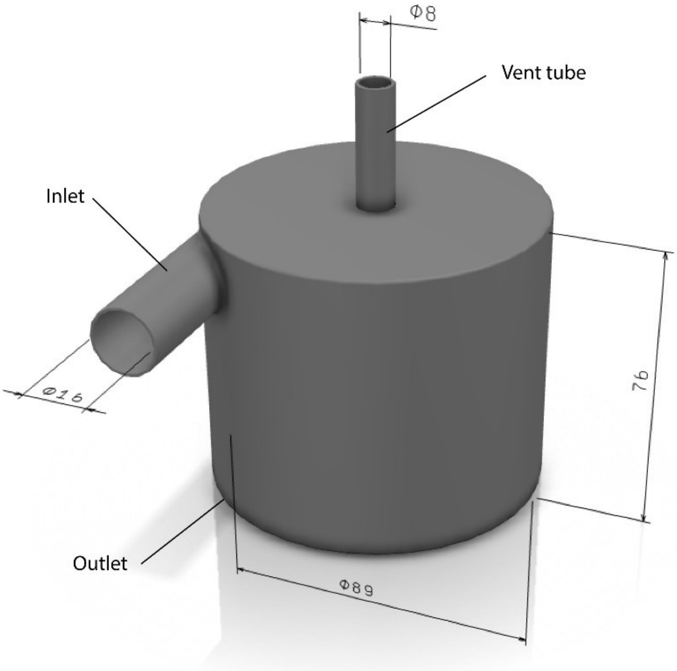

Figure 16: Deaerator with smooth wall- outer configuration

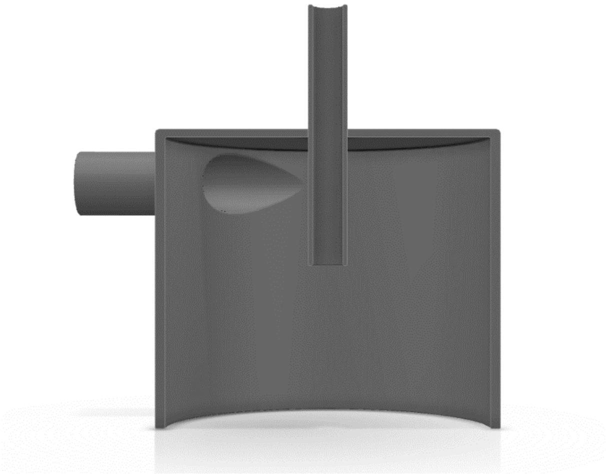

Figure 17: Deaerator with smooth wall- inner structure

II. Deaerator with straight profile of helix

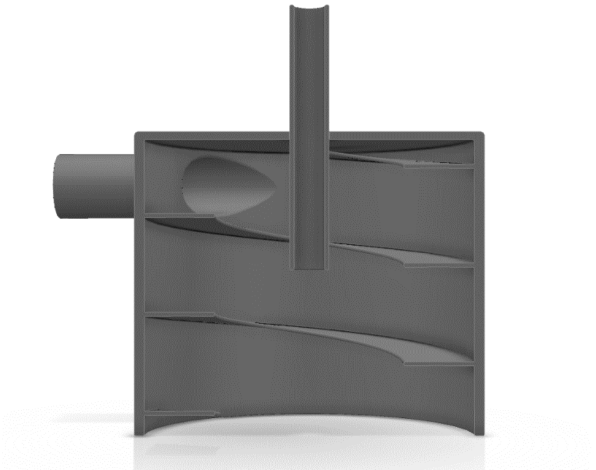

Figure 18: Deaerator with straight profile of helix

III. Deaerator with curved profile of helix

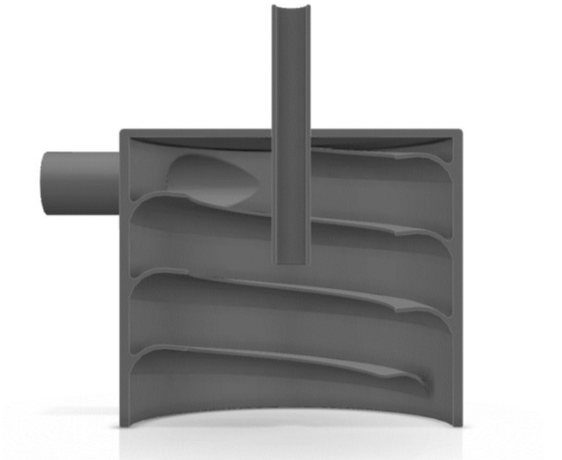

Figure 19: Dearerator with curved profile of helix

5.2. Oil reservoir design

After creating design of separators is necessary to model oil tank for oil storage with following limitations.

Limitations for oil tank design:

1) Volume of the tank with separator should be at least 2,5l
2) Avoid moving oil away from the outlet when accelerating, braking or cornering. This may cause sucking air instead of oil and leads to the loss of oil pressure in engine.
3) Find the lowest position so that centre of gravity of engine would have the lowest position
4) Consider position of separator
5) Separator inlet should be at the top of the tank, oil outlet should be at the bottom of the tank
6) Position and design the shape of the oil tank so that the tank and other parts around it would be accessible in case of maintenance

Design of FS.13 oil tank was divided into four steps:

1. Position and volume

Regards the limitations listed above are possible volumetric locations modelled as seen in the Figures 20 and 21: First one under the differential assembly, another one in the back behind the differential assembly and the last potential area is modelled on the right side between engine and half shaft. Analysis of pros and cons of each modelled region shows that regions behind and under differential do not have sufficient volume and their relatively wide shape might cause dragging oil away from outlet under high g-forces, especially acceleration. On the other hand, location on the right side provides enough space and possibility of much thinner shape of the tank with narrow bottom for constant and correct suction of oil.

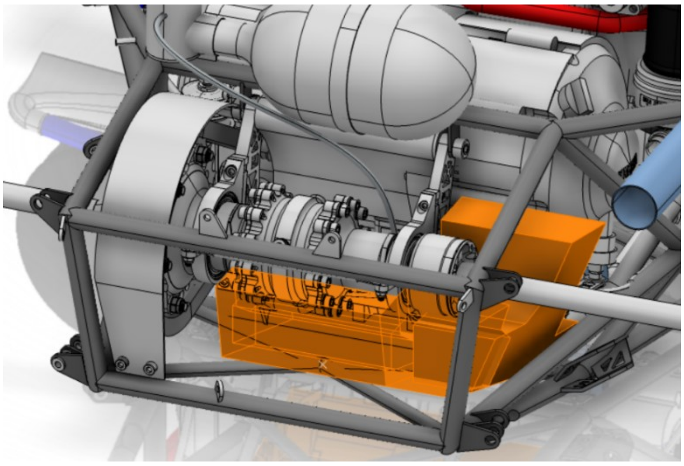

Figure 21: Modelled volumetric regions

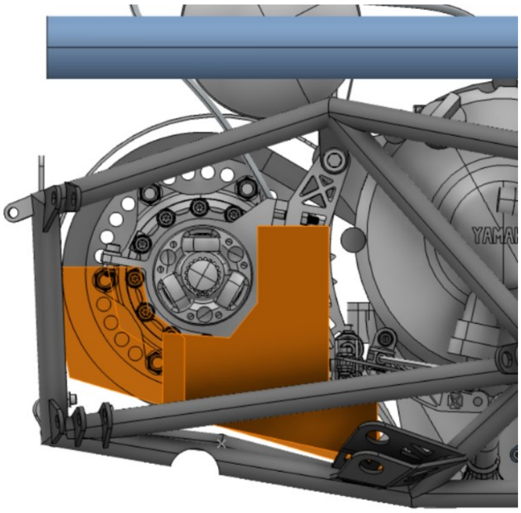

Figure 20: Volumetric regions- right view

2. Basic shape model

After choosing position is first version of model created. In this phase are not modelled inlet and outlet: inlet tube is considered to be placed at the separator with position at the top of the tank and position of outlet must be lowest possible in the narrow part of the bottom section.

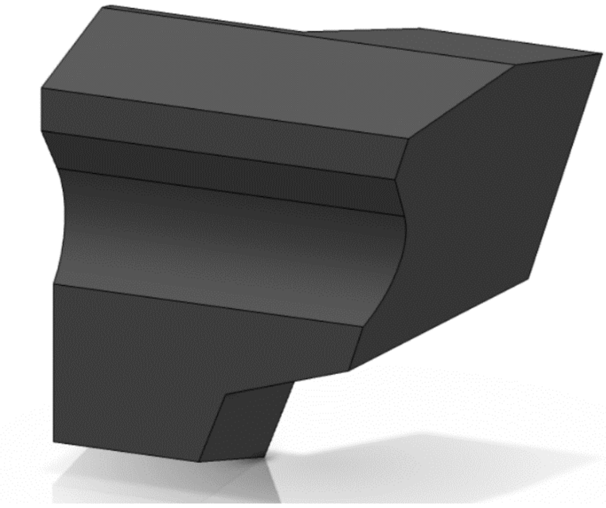

Figure 22: First model of oil tank- back view

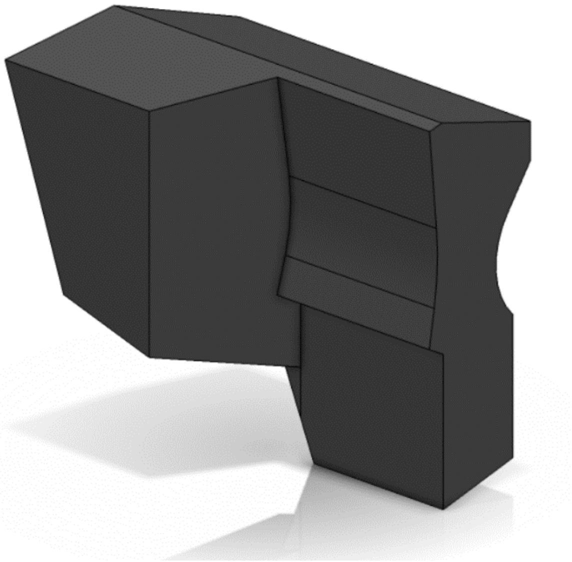

Figure 23: First moedl of oil tank- front view

3. Final shape of oil tank and separator

As described previously cyclone separator for oil deaeration is located at the top of the oil storage tank. Inlet of oil-air dispersion is placed tangentially and horizontally at the top. Cylindrical shape of the separator creates rotational move of the mixture. Oil with higher density rotates downwards on the wall of the main cylinder. Then is stored in the reservoir until it is pumped by high-pressure pump back to engine through horizontally placed outlet at the bottom of the tank. Air accumulates at the centreline of the separator and flows out by vent tube positioned on the axis of the separator. Final volume of oil tank is 2,6l.

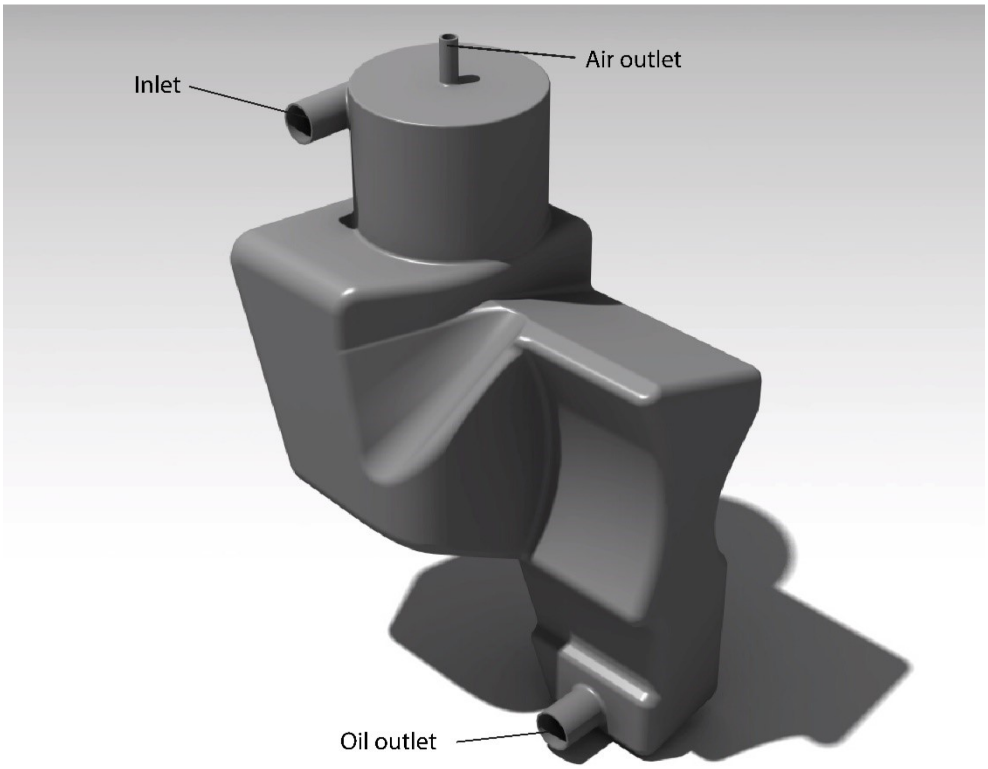

Figure 24: Final shape of oil tank

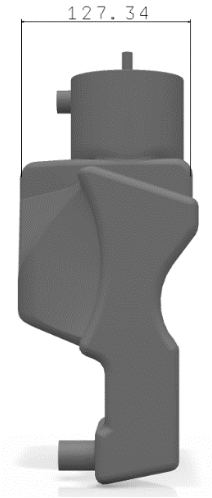

Figure 26: Left view

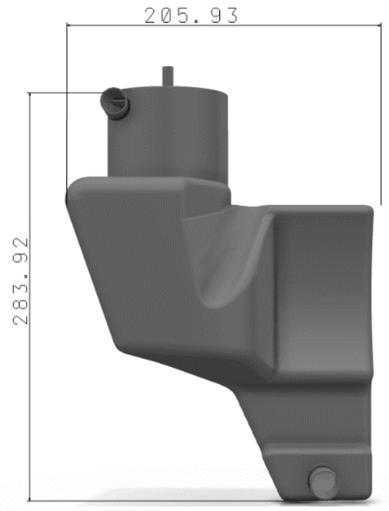

Figure 25: Front view

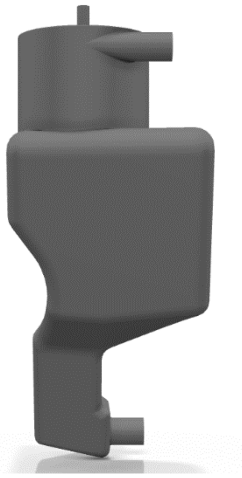

Figure 27: Right view

6. CFD Simulations

Computational fluid dynamics provides opportunity to test functionality of designed part and optimise its shape before it is manufactured physically. The purpose of simulations described below is to simulate oil flow through the separator for variation with smooth wall. For this model is simulated laminar and turbulent flow. Results of the turbulent flow simulation are input values for calculation of separation effectiveness for separator with smooth wall.

In the beginning are Reynolds numbers of oil at inlet and in the main cylinder calculated:

Reynolds numbers at inlet were calculated by expression:

$$Re = \frac{v.d}{\upsilon} \tag{15}$$

where v is tangential velocity at inlet defined from continuity equation:

$$v = \frac{\dot{V}}{S} \tag{16}$$

$\dot{V}$ is volumetric flow through scavenge pump for each engine rpms and S is area of inlet tube. d is diameter of inlet tube and υ is kinematic viscosity of oil at 100°C.

Same expression is used for Reynolds numbers of oil in the main cylinder but S in the continuity equation is area of the main cylinder and d its diameter.

Calculated Reynolds numbers of oil at inlet and in the main cylinder:

Table 13: Reynolds numbers of oil at inlet and in main cylinder of separator

Engine rpm n_m	Re_{oil} inlet	Re_{oil} inside
[1/min]	[-]	[-]
500	343,7	62,7
1000	675,6	125,4
1500	1019,3	188,1
2000	1351,1	250,8
2500	1694,8	313,4
3000	2026,7	376,1
3500	2370,4	438,8
4000	2702,2	501,5
4500	3045,9	564,2
5000	3377,8	626,9
5500	3721,5	689,6
6000	4053,3	752,3
6500	4397,0	815,0
7000	4728,9	877,7
7500	5072,6	940,3
8000	5404,4	1003,0
8500	5748,1	1065,7
9000	6080,0	1128,4
9500	6423,7	1191,1
10000	6755,6	1253,8
10500	7099,3	1316,5
11000	7431,1	1379,2
11500	7774,8	1441,9
12000	8106,7	1504,5
12500	8450,4	1567,2
13000	8782,2	1629,9

As shown in the table, turbulent flow at rpm higher than 6 000 is only at separator inlet, inside the main cylinder is flow laminar.

From the Reynolds numbers of oil at inlet calculated in Table 13 are chosen rpms for laminar and turbulent flow. In the Table 14 below is summarized plan of simulations:

Table 14: Plan of CFD simulations

Separator type	Flow	Engine rpm [1/min]
Smooth wall	Laminar	2 000
	Turbulent	10 000

6.1. Geometry for simulations

In the Figure 28 is shown inner volume of separator that is used for meshing.

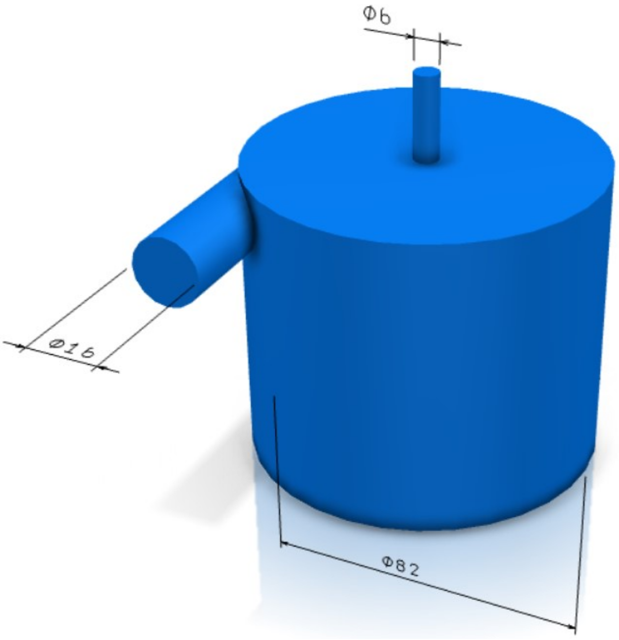

Figure 28: Geometry for numerical simulation

6.2. Mesh and simulation model

Before simulating flow of oil and evaluating results is necessary to find mesh size with the smallest possible number of cells that has minimum influence on solution. Below is described choice of the optimal mesh size with basic overview on mesh parameters, simulation setup and results. Detailed information of each simulation is listed in the Setup section.

For turbulent flow in the separator model with smooth wall are created three meshes in order to examine dependency of solution on the number of cells. Dependency of the mass flow on outlet on the mesh size was extrapolated and for the second mesh with 340 291 cells was calculated grid convergence index about 10^{-5} %. This mesh size is used for simulating model with smooth wall for both laminar and turbulent flow.

Table 15: Dependency of solution on mesh size

	Mesh type	Number of cells	Model	Inlet type	Inlet value
					[kg/s]
1.	polyhedral	177 252	Transition SST	mass flow	0,939747
2.	polyhedral	340291	Transition SST	mass flow	0,939747
3.	polyhedral	575126	Transition SST	mass flow	0,939747

Table 16: Dependecy of mesh size on mass flow

	Method	Iterations	Mass flow inlet	Mass flow outlet	Difference
			[kg/s]	[kg/s]	[kg/s]
1.	Coupled	3000	0,939747	-0,9425256	0,00278
2.	Coupled	3000	0,939747	-0,9397471	$\approx 10^{-7}$
3.	Coupled	3000	0,939747	-0,93974664	$\approx 10^{-7}$

Meshing:

Table 17: Mesh overview

Mesh type	Min. cell size	Max. cell size	Number of cells	Boundary types			
	[mm]	[mm]		Inlet	Outlet 1	Outlet 2	Wall
Polyhedral	0,5	1,2	340 291	Mass flow	Pressure	Pressure	Wall

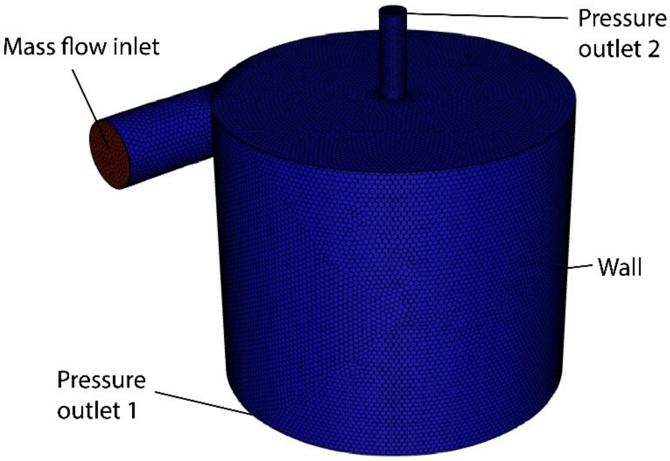

Figure 30: Polyhedral mesh

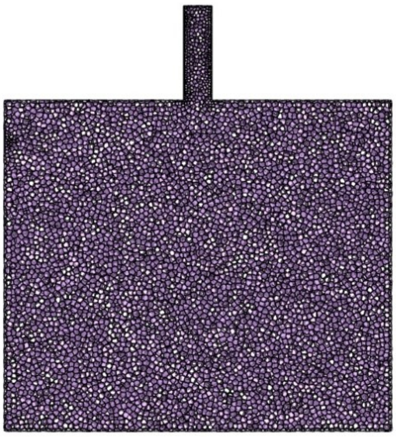

Figure 29: Polyhedral mesh- model cross section

Simulation setup of laminar flow of oil:

Table 18: Simulation setup of laminar flow

Model	Material	Oil		Method	Iterations
	Density	820	[kg/m^3]		
Laminar	Viscosity	0,011644	[kg.m^{-1}. s^{-1}]	Coupled	3 000

Boundary conditions:

Table 19: Boundary conditions of laminar flow simulation

Inlet	Outlet 1	Outlet 2	Wall
Mass flow [kg/s]	Pressure [Pa]	Pressure [Pa]	
0,187944	0	0	Stationary

Simulation setup of turbulent flow of oil:

Table 20: Simulation setup of turbulent flow

Model	Material	Oil		Method	Iterations
	Density	820	[kg/m^3]		
Transition SST	Viscosity	0,011644	[kg.m^{-1}. s^{-1}]	Coupled	3 000

Boundary conditions:

Table 21: Boundary conditions of turbulent flow simulation

Inlet	Outlet 1	Outlet 2	Wall
Mass flow [kg/s]	Pressure [Pa]	Pressure [Pa]	
0,939747	0	0	Stationary

6.3. Results

Laminar flow:

Table 22: Results of laminar flow simulation

Pressure loss [Pa]	Mass flow [kg/s]		
	Inlet	Outlet 1	Outlet 2
302,5	0,187944	-0,187944	-10^{-7}

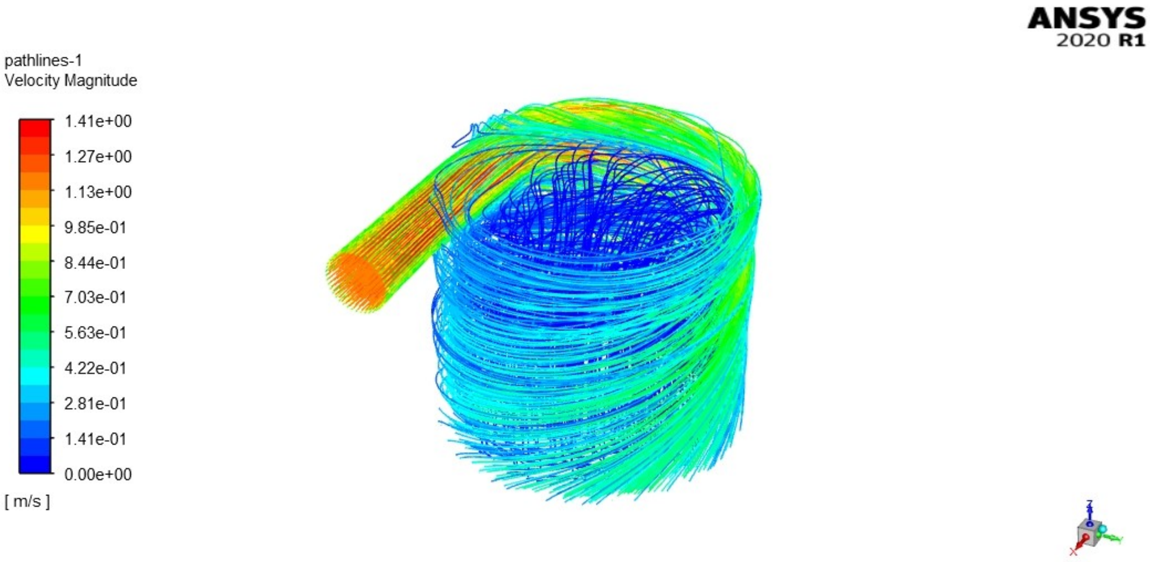

Figure 31: Streamlines of velocity magnitude in laminar flow

Turbulent flow:

Table 23: Results of turbulent flow simulation

Pressure loss [Pa]	Mass flow [kg/s]		
	Inlet	Outlet 1	Outlet 2
3 335,1	0,939747	-0,9397577	$1{,}05 \cdot 10^{-5}$

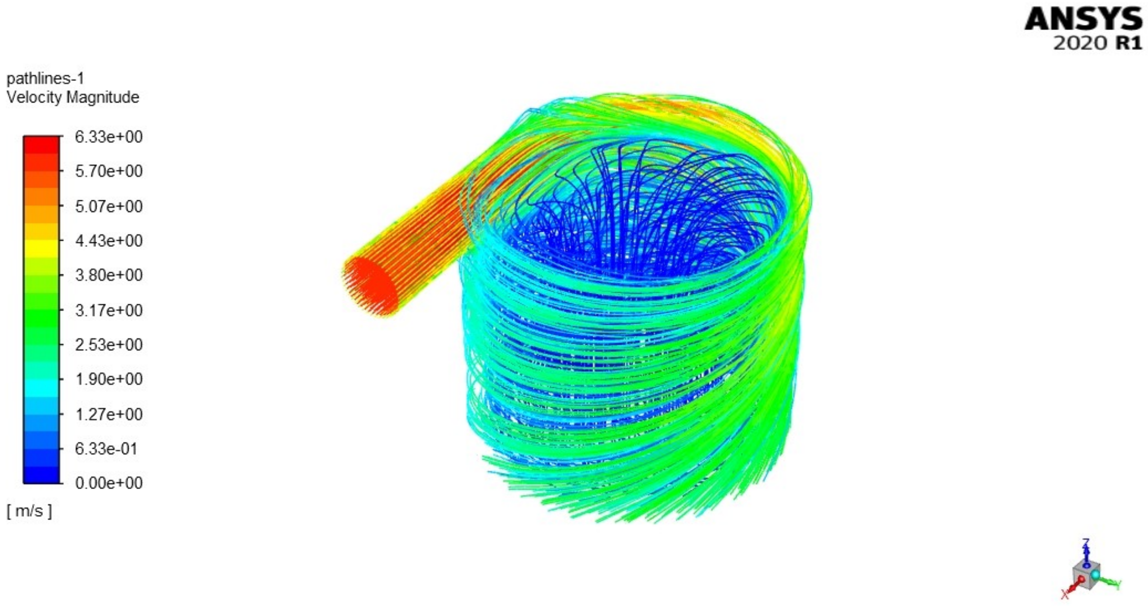

Figure 32: Streamlines of velocity magnitude in turbulent flow

7. Evaluation of effectiveness of centrifugal separation in separator with smooth wall

The purpose of the calculation is to analyse separation of air bubbles in various locations within the separator volume by calculating diameters of separated bubbles in the chosen positions. Diameters of separated air bubbles have to meet two conditions. The first one is that they have sufficient rising velocity to release themselves from the rotational move. The second one is that they must have enough time to reach free surface of rotating oil during its flow through the separator. Input values are based on the results of turbulent flow simulation.

First of all, in each of three horizontal cross sections are defined five points as shown in the Figures 36 and 37. First cross section is located on the centreline of the separator inlet, 61 mm from the bottom of separator. The second one is positioned 40 mm and the last one 20 mm from the bottom.

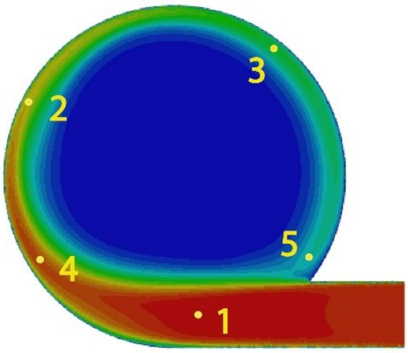

Figure 33: Marked locations of selected points

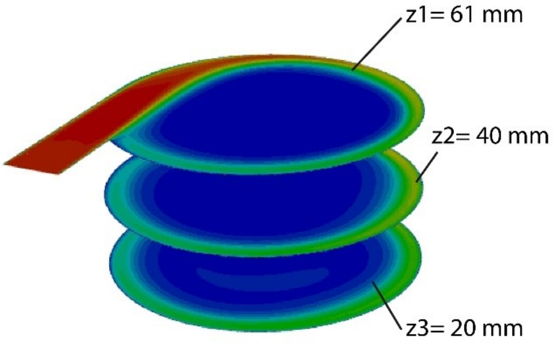

Figure 34: Selected cross sections with z coordinate descriptions

Calculation of bubble diameters is based on equilibrium of forces in the centrifugal field. From simulation results are determined coordinates and velocities in radial and tangential directions of each selected point.

Equilibrium of forces acting on a particle:

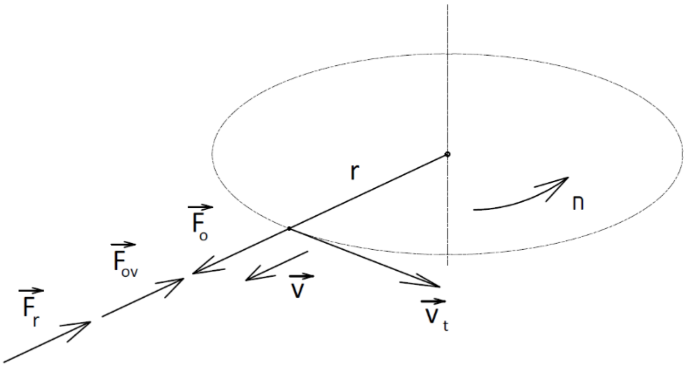

Figure 35: Forces acting on a particle in centrifugal field

$$F_o - F_{ov} - F_r = 0 \tag{17}$$

where each force is defined as:

Centrifugal force:

$$F_o = \frac{\pi \cdot D^3}{6} \cdot \rho_s r \omega^2, \tag{18}$$

D- diameter of observed particle, ρ_s- its density and $r\omega^2$ is centrifugal acceleration.

Buoyancy force in centrifugal field:

$$F_{ov} = \frac{\pi \cdot D^3}{6} \cdot \rho r \omega^2, \tag{19}$$

where ρ is density of fluid.

Drag force of the field:

$$F_r = C_D \cdot \frac{\pi D^2}{4} \cdot \frac{v_r^2}{2} \cdot \rho, \tag{20}$$

v_r - radial velocity, C_D- drag coefficient, for laminar flow inside main cylinder is

$$C_D = \frac{24}{Re}$$

and Re is Reynolds number of fluid defined as:

$$Re = \frac{v_r \cdot D}{\upsilon} \tag{21}$$

After substituting expression of each force, drag coefficient and Reynolds number to equation (17) and expressing diameter D is obtained final equation for bubble diameters

$$D = \sqrt{18 \cdot \frac{\rho v_r^2 \cdot \upsilon}{(\rho - \rho_s) \cdot r\omega^2 \cdot v_t}} \tag{22}$$

in which for particle with lower density than fluid are densities in bracket switched and υ is kinematic viscosity of fluid at 100°C.

Below are described partial calculations and selected parameters of oil and air.

Radius of trajectory:

$$r = \sqrt{x^2 + y^2} \tag{23}$$

x, y are coordinates of the selected point.

Centrifugal acceleration:

$$r\omega^2 = \frac{{v_t}^2}{r} \tag{24}$$

v_t is tangential velocity of particle.

Oil density: $\rho = 820\ kgm^{-3}$

Because of high engine revolutions is chosen air density related to highest pressure in engine.

Air density: $\rho_s = 3{,}26755\ kgm^{-3}$

In the table below are calculated diameters of separated bubbles for the first cross section (z= 61mm) and their Reynolds numbers:

Table 24: Calculated diameters in centrifugal field for z= 61 mm

Position	x	y	r	v_t	v_r	$r\omega^2$	D	Re
	[m]	[m]	[m]	[m/s]	[m/s]	[m/s^2]	[mm]	[-]
1	0,0104	-0,0328	0,0345	6,0027	1,8710	1045,5656	0,6777	54,98
2	-0,0324	0,0218	0,0390	4,1567	0,1025	442,6562	0,2437	1,08
3	0,0276	0,0274	0,0389	2,6938	0,0845	186,4539	0,3410	1,25
4	-0,0322	-0,0213	0,0386	5,4625	0,6841	773,0193	0,4766	14,14
5	0,0336	-0,0165	0,0374	1,9593	0,0984	102,5262	0,4962	2,12

Diameters for z= 40mm:

Table 25: Calculated diameters in centrifugal field for z= 40 mm

Position	x	y	r	v_t	v_r	$r\omega^2$	D	Re
	[m]	[m]	[m]	[m/s]	[m/s]	[m/s^2]	[mm]	[-]
1	0,0159	-0,0330	0,0366	1,7881	-0,0100	87,3859	0,1716	0,07
2	-0,0323	0,0215	0,0388	4,2394	0,0461	462,9441	0,1599	0,32
3	0,0280	0,0271	0,0390	3,1972	-0,0392	262,3912	0,1957	0,33
4	-0,0310	-0,0241	0,0392	3,4612	0,2120	305,4239	0,4221	3,88
5	0,0374	-0,0161	0,0408	1,2792	-0,0071	40,1418	0,2131	0,07

Diameters for z= 20mm:

Table 26: Calculated diameters in centrifugal field for z= 20 mm

Position	x	y	r	v_t	v_r	$r\omega^2$	D	Re
	[m]	[m]	[m]	[m/s]	[m/s]	[m/s^2]	[mm]	[-]
1	0,0154	-0,0320	0,0356	1,5461	-0,0225	67,2205	0,2931	0,29
2	-0,0321	0,0215	0,0387	3,0764	0,0215	244,6458	0,1502	0,14
3	0,0275	0,0274	0,0388	2,9983	-0,0339	231,5080	0,1938	0,28
4	-0,0339	-0,0226	0,0407	1,2477	-0,0177	38,2249	0,3449	0,27
5	0,0331	-0,0166	0,0370	2,1554	-0,0156	125,4141	0,1788	0,12

Calculations show that bubbles with diameter higher than 0,2 mm in cross sections z= 20mm and z= 40mm have potential to be separated from oil. It means that their rising velocity is higher than radial velocity that would keep them rotating in the spinning ring.

Apart from sufficient rising velocity of bubbles to release themselves from rotating oil, they must have time enough to reach free surface of ring during the residence time of oil in the separator. Residence time is calculated from volumetric flow rate of scavenge pump and volume of the created ring:

$$\dot{V} = \frac{V}{t} \qquad \rightarrow \qquad t = \frac{V}{\dot{V}} \tag{25}$$

where volume of rotating ring equals $V = 0{,}116\ l$ and volumetric flow rate through the scavenge pump at 10 000 rpms is $\dot{V} = 1{,}146\ l$. Then residence time of oil in the separator is

$$t = 0{,}22\ s$$

Residence time is substituted to the integration of equation (26):

$$dr = v(r) \cdot dt \tag{26}$$

where

$$v_r(r) = \frac{1}{18} \cdot \frac{D'^2 \cdot r\omega^2 \cdot (\rho - \rho_s)}{\rho \cdot v} \tag{27}$$

is radial velocity expressed form the equilibrium of forces in the centrifugal field for laminar flow inside separator.

Member ω^2 in equation (27) is substituted according to

$$v_t = \omega \cdot r \qquad \rightarrow \qquad \omega = \frac{v_t}{r} \tag{28}$$

v_t is tangential velocity of defined rising bubble and depends on changing radius as bubble rises to the free surface. For this reason, tangential velocity is substituted by mean value defined by tangential velocities in three different radiuses:

$$\bar{v_t} = \frac{v_{t1} + v_{t2} + v_{t3}}{3} \tag{29}$$

After substituting (29) and (28) to (27) and (27) to (26) and integration from initial time $t_0 = 0\ s$ to residence time and from radius of the rotating ring $R_1 = 23\ mm$ to radius of bubble trajectory R_2 and expressing diameter D' is obtained equation for calculation of the diameter in the form:

$$D' = \sqrt{\frac{9 \cdot \rho \cdot \upsilon}{(\rho - \rho_s) \cdot \bar{v_t}^2 \cdot t} \cdot (R_2^2 - R_1^2)} \tag{30}$$

Diameters calculated from residence time for z= 40mm:

Table 27: Calculated diameters from residence time for z= 40mm

Position	x	y	r	v_t	v_r	$r\omega^2$	D'
	[m]	[m]	[m]	[m/s]	[m/s]	[m/s^2]	[mm]
1	0,0159	-0,0330	0,0366	1,11	-0,0100	87,3859	0,6198
2	-0,0323	0,0215	0,0388	2,52	0,0461	462,9441	0,2991
3	0,0280	0,0271	0,0390	2,04	-0,0392	262,3912	0,3715
4	-0,0310	-0,0241	0,0392	2,26	0,2120	305,4239	0,3388
5	0,0374	-0,0161	0,0408	0,83	-0,0071	40,1418	0,9812

Diameters for z= 20mm:

Table 28: Calculated diameters from residence time for z= 20mm

Position	x	y	r	v_t	v_r	$r\omega^2$	D'
	[m]	[m]	[m]	[m/s]	[m/s]	[m/s^2]	[mm]
1	0,0154	-0,0320	0,0356	0,92	-0,0225	67,2205	0,7129
2	-0,0321	0,0215	0,0387	1,51	0,0215	244,6458	0,4951
3	0,0275	0,0274	0,0388	2,04	-0,0339	231,5080	0,3702
4	-0,0339	-0,0226	0,0407	1,06	-0,0177	38,2249	0,7640
5	0,0331	-0,0166	0,0370	1,43	-0,0156	125,4141	0,4888

As numerical simulations were set up only for flow of oil without modelling surface of created ring, computed tangential velocities are significant lower in comparison to the simulation where shape of free surface would be considered. This reflects in higher calculated diameters of bubbles opposite to those actually separated and lower effectiveness of separation.

If the mean tangential velocity was equal to inlet tangential velocity in entire volume of the separator

$$\overline{v_t} = 5{,}42\ ms^{-1}$$

then diameter of separated bubble on the wall of the separator with radius $r = 0{,}041\ m$ would be approximated to

$$D' = 0{,}15\ mm$$

Comparison of calculated diameters according to both conditions shows that bubbles with diameters higher than 0,4 mm are certainly separated from oil by centrifugal separation, regards the distortion of values calculated from second condition.

In reality can be likely assumed that rotating ring forms with significantly higher tangential velocities with values near to tangential velocity at separator inlet. In these circumstances minimal diameter of separated bubbles would be 0,15 mm which means that real separation effectiveness would be higher than that calculated from numerical simulations. According to this fact are in the separator with smooth wall separated bubbles with diameters higher than cca 0,25 mm.

8. Manufacturing

There are two possible material options for oil tank with parameters listed in the Table 29 below:

Table 29: Analysis of materials and manufacturing methods

Material	Aluminium- EN AW 6063	Plastic
Manufacturing method	welding, bending, laser cutting	3D printing
Min material thickness	1 mm	5 mm
Temperature resistance at least 150°C	Yes	Yes
Estimated weight	0,5 kg	0,3 kg
Advantages	- previously used - heat resistant, oil resistant	- variability of materials - sponsorship from external supplier - not limited in shape
Disadvantages	- professional welding skills - all dimensions must be kept as designed because of relatively small space between oil tank, other engine parts and frame tubes - shape of the tank is limited by bend radius, flat metal sheets	- never done before - special material properties regarding strength and temperature and chemical resistance

As results from comparison advantages of aluminium are stiffness, weight, small wall thickness and heat resistance. On the contrary its biggest disadvantages are manufacturing process as it requires advanced welding skills and shape of the tank is limited to simple curvatures and flat surfaces.

We have decided for 3D printed plastic oil tank as the team was offered sponsorship for 3D printed parts. Moreover, this method requires no welding skills, guarantees better precision of dimensions and shape of manufactured model, and offers variability of specific plastic materials to choose from.

9. Oil tank design for engine test stand

Before using oil tank and separator on the car, is necessary to examine functionality and effectiveness of each designed separator modification on engine test stand. For this purpose, is designed oil tank with simplified shape and joints for easy changeability of separators. Furthermore, are models of separators adjusted for joining with oil tank.

Requirements on engine test stand oil tank:

a) simple shape
b) joints with sealing for separator replacement
c) opening for plexiglass for observation of separation process inside the tank
d) supports for positioning, handles for fastening

Requirements on separator adjustments:

a) made of transparent material
b) joints for connection with oil tank

Material and manufacturing method:

As manufacturing method for tank and separators for the test stand was chosen 3D printing. Then were chosen possible plastic materials with suitable parameters as chemical resistance to oil and temperature resistance at least 150°C. For testing separators was also essential to find transparent material. Finally, was for oil tank and separators chosen the same material Figure 4 HI TEMP 300-AMB with characteristics as stated in the Table 30.

Selected characteristics of Figure 4 HI TEMP 300-AMB:

Table 30: Charcteristics of material Figure 4 HI TEMP 300-AMB [11]

Tensile strength	75 MPa
HDT 1,82MPa	>300°C

Final models of oil tank and adjusted separators for engine test stand:

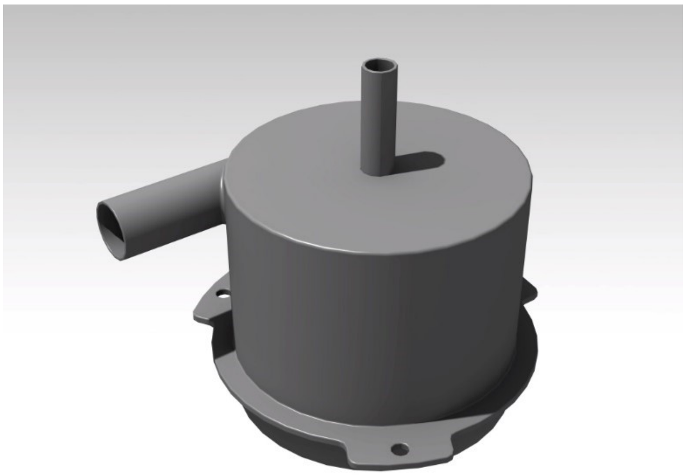

Figure 36: Model of adjusted separator

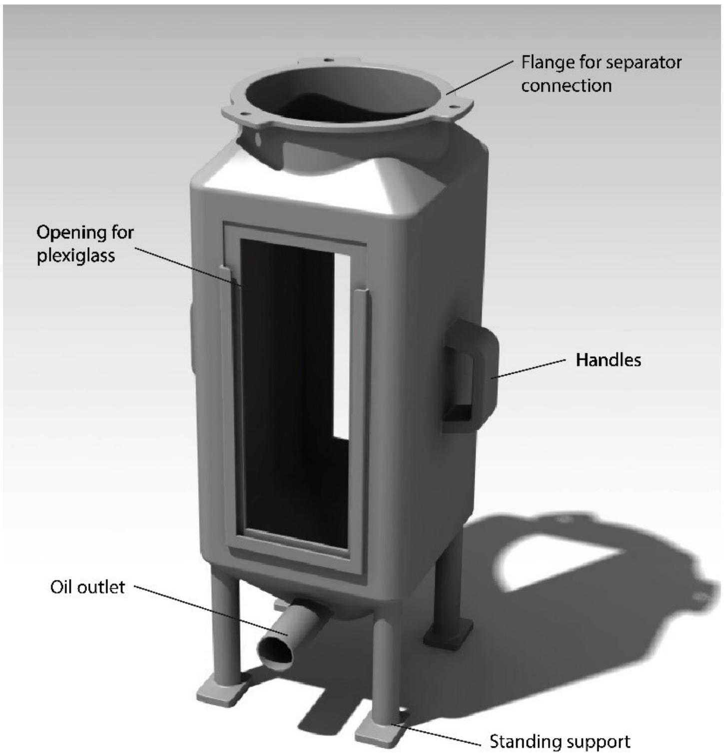

Figure 37: Oil tank for engine test stand

Conclusion

The purpose of this bachelor thesis was to design oil tank for dry sump lubrication system of Formula Student car. Design was divided into the following steps:

- In the beginning was described design of FS.12 oil tank and reasons for new oil tank design as relocation between engine and frame and increase effectiveness of separation.
- Firstly, was carried out research on problem. In the research were explained two separation methods, gravitational and centrifugal. Various examples of commonly manufactured oil tanks showed that they use centrifugal method for separation of air bubbles.
- For new oil tank design was necessary to evaluate whether gravitational separation is sufficient to separate air bubbles of specified diameters. Calculations proved that bubbles with diameters higher than 1 mm are separated by gravitational principle. That demonstrates need of another separation method.
- In the next part were compared two centrifugal separators, cyclone separator and in-line separator. From comparison resulted that cyclone separator is more suitable option for this type of application. Afterwards was designed model of cyclone separator in three configurations: model with smooth wall, with straight profile of helix and curved profile of helix. Apart form separator models, was model of storage tank created.
- As were calculations of air bubble separation in gravitational field carried out so was necessary to calculate in centrifugal field. Firstly, was by CFD simulations computed laminar and turbulent flow for model of separator with smooth wall. Values of radial and tangential velocities in selected locations were obtained from turbulent flow simulation. For all separated bubbles were given two conditions. The first one was that their rising velocity was sufficient to release themselves from the rotational move. The second one was that they had to reach free surface of rotating oil in shorter period than is its residence time in separator. According to first condition were from equilibrium of forces acting on a particle in the centrifugal field calculated diameters of separated bubbles in specified locations. According to the second condition were from residence time of oil and mean tangential velocity for each bubble calculated another set of diameters. Calculation of diameter for inlet tangential velocity showed distortion in previously calculated values. Numerical simulating without considering the level of oil ring caused decrease of tangential velocities which resulted in higher diameters of separated bubbles and hence reduced separator effectiveness. Comparison of diameters calculated from both conditions,

regards the distortion, proved that bubbles with diameter higher than 0,25 mm have sufficient rising velocity and enough time to release from oil.

- From evaluation of gravitational and centrifugal separation results that the separator with smooth wall is suitable for separation of air bubbles with diameter higher than 0,25 mm. This value is satisfactory for this type of application according to defined diameters in the beginning of the calculations of gravitational principle.
- Increased or more accurate effectiveness can be obtained from: simulation with definition of level function, simulations and calculations of two other separator variations or model modification- increase of the main cylinder diameter.
- In the end of the thesis was described design of oil tank for engine test stand that brings another way of validation of the designed separators.
- The thesis was concluded by analysis of manufacturing methods and materials. Chosen manufacturing method was 3D print from plastic with suitable parameters according to requirements.

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