TALLINNA TEHNIKAÜLIKOOL
MEHAANIKATEADUSKOND

MEHHATROONIKAINSTITUUT

Mehhanosüsteemide komponentide õppetool

MHE70LT

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Värvimiskambri automaatne ventilatsioonisüsteem

MSc Lõputöö

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akadeemilist kraadi

Tallinn
2016

TALLINNA TEHNIKAÜLIKOOL
MEHAANIKATEADUSKOND

Department of Mechatronics

Chair of Mechanosystem Components

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Automatic ventilation system for painting chamber

Master's Thesis

Author applying for
master's sciences of technical
academic degrees

Tallinn
2016

AUTHOR'S DECLARATION

I declare that I have written this graduation thesis independently.

These materials have not been submitted for any academic degree.

All the works of other authors used in this thesis have been referenced.

The thesis was completed under .... supervision
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The thesis complies with the requirements for graduation theses.

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Supervisor

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Accepted for defence.

.... chairman of the defence committee

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TUT Department of Mechatronics

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MASTER'S THESIS TASK

Year 2015/16 Spring semester

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Study programme: Mechatronics, MAHM02/13

Spetsiality: Mechatronics………………………

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MASTER'S THESIS TOPIC:

(in English) **Automatic ventilation system for painting chamber**…………....

(in Estonian) **Värvikambri automaatne ventilatsioonisüsteem** ………………

Assignments to be completed and the schedule for their completion:

Nr	Description of the assignment	Completion date
1.	Overview of automatic ventilation systems available in the market. Comparison of different automatic ventilation systems and their parameters. Definition of technical parameters of automatic ventilation system (type, dimensions, power etc).	01.02.2016
2.	Required air flow calculation. Fan power and ventilation pipe cross section calculation. Heater power calculation.	15.02.2016
3.	Ventilation automatization system development. Air masses flow, temperature and air humidity adjustment and control.	01.03.2016
4.	Technical drawings of ventilation system. Cost calculation of developed ventilation system.	30.03.2016
5.	Printing and binding of Master's thesis.	15.05.2016

Engineering and economic problems to be solved: In this Master's thesis the automatic ventilation systems should be developed. Ventilation systems should have the adjustable air masses flow, temperature and air humidity control system. Project cost calculations should be done. Ventilation system should meet required environmental parameters.

Additional comments and requirements: ….…………………………….............................

Language: English

Deadline for submission of the application for defence 16.05.2016

Deadline for submitting the theses 16.05.2016

Student Pavel Zibarov…………. /signature/ ……….............date ………

Supervisor Alina Sivitski……/signature/ ……….............. date………

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Table of contents

List of figures and tables

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Eessõna

Selle magistritöö teema on pakutud inimese poolt, kes tahab renoveerida enda värvimiskambri ja paigaldada kaasaegset automaatset ventilatsiooni. Praegusel värvimiskambril on kasutusel ainult väljatõmme ventilaator, mille võimsusest ei piisa värvimiskambri efektiivseks ventileerimiseks. Tulemuseks, detailide kuivatamine võtab palju aega ja värvimiskamber on keemia lõhna täis. Vaatmata sellele, et on võimalik osta uut kokkupantud ventilatsiooni, see on liiga kallis. On otsustatud projekteerida uut ventilatsioonisüsteemi.

Värvimiskambrites, ventilatsioon on mõeldud värviaurude ja tolmu eemaldamiseks, mis võimaldab teostada kvaliteetset värvimist. Teiseks, effektiivne ventilatsioon kiirendab kuivamisprotsessi. Lisaks, ventilatsioonisüsteem sisaldab filtride ahelat, mis püüab kinni selliseid saasteaineid, nagu keemiaaurud, mis on mürgised ja mõjuvad mitte ainult keskkonda, vaid inimeste tervist ka.

Tööülesanne on projekteerida kaasaegset ventilatsioonisüsteemi konkreetse värvimiskambri jaoks maksimaalse efektiivsusega ning minimaalse ressurside kulutamisega.

Foreword

Topic of the thesis was offered by a person, who wants to renovate his paintig chamber and establish modern automatic ventilation system. In current ventilation, exhaust fan is used, which do not have enough power to ventilate painting chamber. As a result, drying of details takes a lot of time and the smell of the paint is all over the chamber. Despite the fact, that it is possible to buy a new assembled ventilation, it is too expensive, so it was decided to design a new ventilation system.

In painting chambers, ventilation systems are meant to remove paint vapors and dust, creating favorable conditions for painting and to accelerate drying time. In addition, it contains a system of filters to absorb all pollution elements, such as paint vapors, which are poisonous and affect not only on environment, but also on health of workers.

The aim of the work is to design a modern automatic ventilation system for a particular chamber with a minimum electricity consumption and maximum ventilation efficiency.

Introduction

Ventilation system for painting chamber consists of fans, filters, heater, regulation valves and duct. Designing of a ventilation system starts with choice of ventilation type. This choice is based on a task, that ventilation have to perform well and is affected by price and effectiveness of ventilation. After ventilation type is chosen, it is necessary to calculate required air flow for the chamber. Air flow calculation is based on chamber dimensions and allows to choose proper cross section for the duct and calculate required capacity for heater. Basing on dimensions of the duct, it is possible to calculate air resistance and choose proper fans with required parameters. After all calculations are obtained, it is possible to model ventilation system for the chamber – it helps to orientate in created construction and assess, how the ventilation have to be automated. Automatization is required for effective control of air flows, which is necessary for qualitative car painting. After automatization is completed, the price of designed construction can be calculated.

To complete the task, the following softwares are used: environment for drawing making – AutoCAD, environment for 3D modelling – Solid Edge, environment for PLC programming – Mitsubishi Alpha and program to publicate represented work – Microsoft Word.

Main part

1. Ventilation review

1.1 Ventilation types

There are a lot of different ventilation systems. The difference is in area of use and also in working principle. So,first of all, it is necessary to define, what kind of ventilation type is required for painting chamber. There are 3 main types of ventilation: supply-, exhaust and balanced ventilation systems.

1) Supply ventilation – provides only air inflow in room. Air outflow is made through the gaps in room. Supply ventilation can be made using fan – forced ventilation, or without – natural ventilation. This type of ventilation is used mostly in living houses or offices: places, where air is not getting polluted quickly.

Advantages: simple construction, low cost.

Disadvantages: low efficiency of the ventilation.

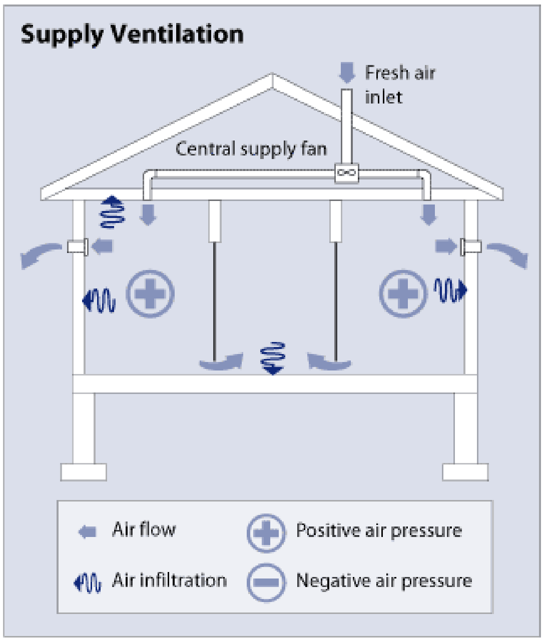


Fig. 1. Supply ventilation [1]

2) Exhaust ventilation – provides only air outflow. Air inflow is caused due to pressure difference, which is formed by outflow. Exhaust ventilation is achieved using fans. This type of ventilation is used in small rooms, where it is necessary to remove air quickly: kitchens, laboratories.

Advantages: fast removal of exhaust air.

Disadvantages: effective only in small rooms.

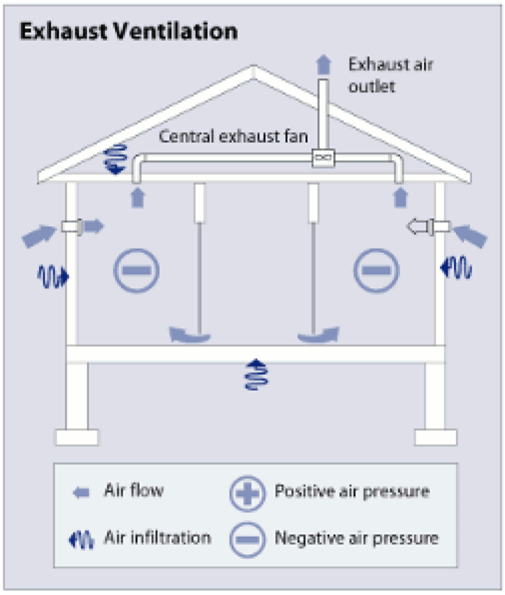


Fig. 2. Exhaust ventilation [1]

3) Balanced ventilation – incorporates both supply and exhaust ventilation. Such ventilation system is able to effectively remove exhaust air and, at the same time, supply room with fresh air. This type of ventilation is used in buildings, where productive circulation of air is necessary: factories, concert buildings, supermarkets.

Advantages: high efficiency of the ventilation.

Disadvantages: high cost, high electricity consumption.

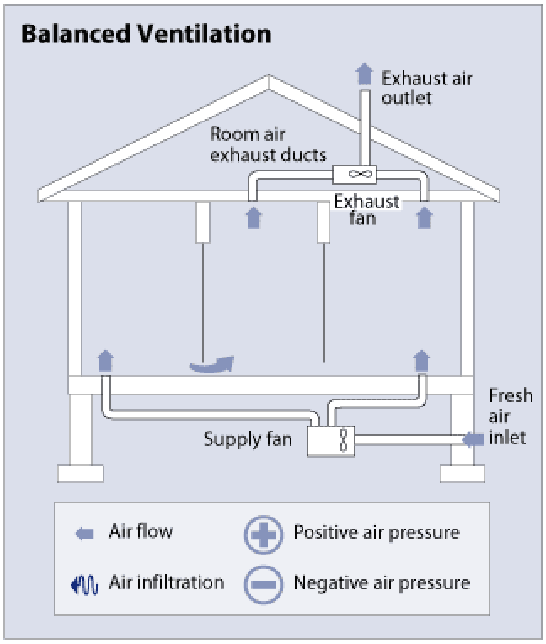


Fig. 3. Balanced ventilation [1]

To choose a proper ventilation system for the painting chamber, it is necessary to analyze all aspects, required for car painting. First of all, it is very important to have clear air while painting to avoid hitting of dust on painted surface. It means, that inflow of clear air is required, so supply ventilation will be needed. Secondly, paint vapors are poisonous and have to be removed from chamber. For effective removal of polluted air, exhaust ventilation is necessary. As a result, balanced ventilation is required. Despite the fact, that it is the most expensive type of ventilation, it is also the most effective and painting chamber is a room, where ventilation effectiveness is the most important.

1.2 Overview of ventilation systems available on the market

As it was said before, current ventilation system used in workroom, is not effective enough. Required productivity of painting chamber is about 50 cars per month. There are two solutions for the problem:

1) It is possible to buy already assembled painting chamber

There are two most common companies offering painting chambers on Estonian market:

a) “Blowtherm” – it is the Italian company, famous for its high quality of the product. Painting chamber, meeting all requirements, called „New World“. Available air heating sources are gas or diesel. Price for this painting chamber with introduced characteristics is 22,999 € [2] and it could slightly vary depending on the supplier.

Parameters	
Dimensions	(4x7x2.7) m
Heater power	269 kW
Fuel type	Gas/Diesel
Supply fan power	7,5 kW
Exhaust fan power	7,5 kW
Air flow rate	24000 m^3/h

Fig.4. “Blowtherm” painting chamber [2]

b) “Wolf” – it is a german company, famous for its innovation technologies. Painting chamber, meeting all requirements, called “Taifuno WFW 180”. Available air heating sources are gas, diesel or water. Price for this painting chamber with introduced characteristics, using gas or diesel, is 24,500 € [3] and it could slightly vary depending on the supplier. Cost of painting chamber, using water for air heating, is significantly higher.

Parameters	
Dimensions	(4.1x7.9x2.6) m
Heater power	265 kW
Fuel type	Gas/Diesel/Water
Supply fan power	2x2,5 kW
Exhaust fan power	2x2,5 kW
Air flow rate	19000 m^3/h

Fig.5. “Wolf” painting chamber [3]

Also, it is useful to investigate china market, because the variety of painting chambers is wide and prices are more friendly. A website, offering chinese industrial equipment, called „www.alibaba.com“ shows the price range between 10,000 – 15,000 € on painting chambers. It should be kept in mind, that there is no confidence in reliability of chinese painting chambers, still, as a price comparison, it is good example.

2) Construct ventilation system in already existing work room

Main barrier for the first solution is price. There is reasonable suspicion, that assembled painting chamber is significantly more expensive, than construction of the ventilation in already existing workroom, so it is considered to try second solution and check, how profitable this variant is.

2. Primary calculations

2.1 Air flow calculation

Development of ventilation scheme starts with calculation of required power for fans. To determine characteristics of the fan, air flow rate (C, m^3/h) – value, characterizing the air supply to the room per unit of time, needs to be found. This parameter can be calculated by the following formula:

$$C = S \cdot V \ [4]$$

Where,

S – area of a painting chamber

V – air flow velocity

According to European Standard EN13355 [5], minimal air flow velocity in painting chamber should be 0,3 m/s = 1080 m/h, which is comparable with ISO 146144-1 3rd cleanliness class (Tab.1).

Tab.1. ISO 146144-1 - airflow velocities and air change rates [6]

Class ISO 146144-1 (Federal Standard 209E)	Average Airflow Velocity m/s (ft/min)	Air Changes Per Hour	Ceiling Coverage
ISO 8 (Class 100,000)	0.005 – 0.041 (1 – 8)	5 – 48	5 – 15%
ISO 7 (Class 10,000)	0.051 – 0.076 (10 -15)	60 – 90	15 – 20%
ISO 6 (Class 1,000)	0.127 – 0.203 (25 – 40)	150 – 240	25 – 40%
ISO 5 (Class 100)	0.203 – 0.406 (40 – 80)	240 – 480	35 – 70%
ISO 4 (Class 10)	0.254 – 0.457 (50 – 90)	300 – 540	50 – 90%
ISO 3 (Class 1)	0.305 – 0.457 (60 – 90)	360 – 540	60 – 100%
ISO 1 – 2	0.305 – 0.508 (60 – 100)	360 – 600	80 – 100%

Fig.6. Dimensions of the painting chamber

Dimensions of painting chamber is 3,05m x 5,94m = 18,1 m^2 (Fig.6)

So the air flow rate is:

$$C = 18{,}1 \times 1080 = 19548 \frac{\mathrm{m}^3}{\mathrm{h}} = 5{,}43 \frac{\mathrm{m}^3}{\mathrm{s}}$$

2.2 Calculation of the duct

Proper calculation of dimensions for the ducts is very important. Duct cannot be too big, because it is expensive and take a lot of room and it cannot be too small, because it causes a big load on construction and do not provide the room with required air flow. For painting chamber two shapes of duct are used: circular and rectanglular ducts. Circular duct is better, because it has lower aerodynamic resistance and since there is no angles, it does not gather dust. However, quite often, there is no enough space to place circular ducts, so it is the reason, why rectanglular ducts are used.

First of all, required dimensions should be calculated, as it is necessary to determine cross section of the duct. Cross section of the duct can be calculated as:

$$A = \frac{\mathrm{C}}{\mathrm{v}} \; [7]$$

Where:

A - duct cross sectional area (m^2)

C - air flow rate (m^3/s)

v - air velocity (m/s)

From the equation is clear, that the greater velocity is, the lower cross section is needed. But it is not a good idea to boost air velocity in the duct, because it causes noise and high pressure in ventilation. Proper air velocity should be chosen wisely, so there is nothing left, but turn to air velocity recommendation table (Tab.2).

Tab.2. Recommended air velocities [8]

Air Flow Rate		Maximum Velocity	
(m^3/h)	*(CFM)*	*(m/s)*	*(ft/min)*
< 5,000	< 2,950	10	2,000
< 10,000	< 5,900	12	2,350
< 17,000	< 10,000	15	2,950
< 25,000	< 14,700	17	3,350
< 40,000	< 23,500	20	3,940

Based on the table, cross section can be calculated now:

$$A = \frac{C}{v} = \frac{5{,}43}{17} = 0{,}32\ \mathrm{m}^2$$

When cross section is calculated, it is possible to calculate dimensions for the duct:

Diameter for circular duct can be calculated as:

$$A = \pi(\frac{d}{2})^2 \rightarrow d = 2 \times \sqrt{\frac{A}{\pi}} = 2 \times \sqrt{\frac{0{,}32}{\pi}} = 0{,}63\ \mathrm{m}$$

There is standard dimensions for ventilation duct, so to choose real dimension, followed table is used:

Tab.3. Circular Duct Dimensions [9]

Nominal Diameter *(mm)*	Outside Diameter *(mm)*	Inside Diameter *(mm)*
63	63 - 63.5	61.8 - 62.3
80	80 - 80.5	78.8 - 79.3
100	100 - 100.5	98.8 - 99.3
125	125 - 125.5	123.8 - 124.3
160	160 - 160.6	158.7 - 159.3
200	200 - 200.7	198.6 - 199.3
250	250 - 250.8	248.5 - 249.3
315	315 - 315.9	313.4 - 314.3
400	400 - 401.0	398.3 - 399.3
500	500 - 501.1	498.2 - 499.3
630	630 - 631.2	628.1 - 629.3
800	800 - 801.6	798.0 - 799.3
1000	1000 - 1002.0	997.9 - 999.3
1250	1250 - 1252.5	1247.8 - 1249.3

To ensure required parameters, dimensions are rounded to the closest greater number. So the diameter of circular duct is 630 mm.

Dimensions of rectanglular duct can be calculated as:

$$A = a \times b$$

To calculate dimensions for rectanglular duct, one of the sides have to be defined. This type of duct is used in places with limited room. In a case with painting chamber, this place is ceiling space, so duct width should be as minimum as possible. To define minimum possible width, standard dimension table is used:

Tab.4. Dimensions of common rectangular air ducts used in ventilation systems [10]

Width (mm)	Height (mm)										
	100	150	200	250	300	400	500	600	800	1000	1200
200	1)	1)	2)	3)	3)	3)	3)	3)	3)	3)	3)
250	2)	2)	2)	2)	3)	3)	3)	3)	3)	3)	3)
300	1)	1)	1)	2)	2)	3)	3)	3)	3)	3)	3)
400	1)	1)	1)	2)	1)	2)	3)	3)	3)	3)	3)
500	3)	1)	1)	2)	1)	1)	2)	3)	3)	3)	3)
600	3)	1)	1)	2)	1)	1)	1)	2)	3)	3)	3)
800	3)	3)	1)	2)	1)	1)	1)	1)	2)	3)	3)
1000	3)	3)	3)	2)	1)	1)	1)	1)	1)	2)	3)
1200	3)	3)	3)	3)	1)	1)	1)	1)	1)	1)	2)
1400	3)	3)	3)	3)	3)	2)	2)	2)	2)	2)	2)
1600	3)	3)	3)	3)	3)	1)	1)	1)	1)	1)	1)
1800	3)	3)	3)	3)	3)	3)	2)	2)	2)	2)	2)
2000	3)	3)	3)	3)	3)	3)	3)	3)	1)	1)	1)

1) Preferred, 2) Acceptable, 3) Not common

Now, it is possible to choose proper dimensions:

$$a = \frac{A}{b} = \frac{0{,}32}{0{,}4} = 0{,}8 \text{ m}$$

To ensure required parameters, dimensions are rounded to the closest greater number. So the dimensions of rectangular duct are (400x800) mm.

2.3 Heater capacity

Heater in ventilation system is a device, that heats incoming air. Heater in ventilation of painting chamber is very important – it heats the temperature of incoming air. It is necessary for qualitative painting and quick drying. To start calculation, it is necessary to define required temperature for painting, which is 22 ºC [5] and minimum rated temperature of outside air, which is, according to Estonian standard EVS 844:2016, established as -25 ºC [11]. When all the data is obtained, power of the heater can be calculated as:

$$P = \Delta T \times G \times q \text{ [12]}$$

Where:

P – power of the heater (W)

ΔT – difference between minimum and maximum temperature (°C)

$$\Delta T = T_{max} - T_{min} = 22 - (-25) = 47\text{°C}$$

q - specific heat capacity ($\frac{J}{kg \times K}$) – this value is based on minimum temperature of incoming air (-25 ºC) and equals to 1009 $\frac{J}{kg \times K}$ (Tab.5)

Tab.5. Specific heat capacity of air [12]

T,ºC	- 25	- 20	- 15	- 10	- 5	0	+ 5	+ 10	+ 15	+ 20	+ 25
q,J/(kg*K)	1009	1008	1007	1007	1006	1005	1005	1005	1005	1005	1005

G - mass flow of heated air $\frac{kg}{s}$

$$G = C \times \rho = 4{,}32 \times 1{,}3 = 5{,}62\ \frac{kg}{s}\ [12]$$

C – air flow rate $\frac{m^3}{s}$

ρ – density of air at a -1,5 ºC $\frac{kg}{m^3}$

-1,5 ºC is an average of maximum and minimum temperature:

$$T_{avr} = \frac{22 - 25}{2} = -1{,}5\ ℃$$

Density of air at -1,5 ºC is obtained from Tab.6 and equals to 1,3 $\frac{kg}{m^3}$

Tab.6. Density of air at different temperatures [12]

T,ºC	- 15	- 10	- 5	0	+ 5	+ 10	+ 15
ρ,kg/m³	1.37	1.34	1.32	1.29	1.27	1.25	1.23

Now, when all necessary data is obtained, power of the heater can be calculated:

$$P = 47 \times 5{,}62 \times 1009 = 266517\ W \approx 266{,}5\ \text{kW}$$

After the power is calculated, it is possible to choose proper type of heater. There are three main types of heater for ventilation in painting chambers: electric, gas and diesel heaters.

Electric heater uses heating elements, which convert electric energy into heat. Electric heaters are compact and installation is cheap. However, electric heaters have high consumption of electricity and are used mostly in small, home-made painting chambers, where no need to heat a big amount of air.

Advantages: compact, inexpensive installation, low fire hazard

Disadvantages: high exploitation costs

Gas heater uses gas as a fuel for heating air. Gas heater can work on natural gas and on liquefied gas. It has high specific power and quickly heats air. Also, gas, as energy sourse is not as expensive as electricity. However, installation cost is high and it is not the safiest heater because of high fire hazard.

Advantages: low exploitation costs

Disadvantages: expensive installation, high fire hazard

Diesel heater is a good alternative to gas heater. It is very similar to gas heater, but less of a fire hazard. However, diesel is more expensive than gas and there is no diesel lines to connect.

Advantages: low fire hazard

Disadvantages: high exploitation costs

Since required power is high, electric heater is not suitable, because it consumes a lot of electricity. Gas pipes are not held to the house, where painting chamber is, but gas station is near, so it is possible to obtain both diesel and liquefied gas. Gas is cheaper than diesel, but heater installation is more expensive. Exploitation costs are the lowest using gas heater, with constant use of painting chamber, economy on fuel is great, so, basing on the lowest exploitation costs, gas heater is chosen.

Air heater consisnts of two main parts: heat exchanger and burner (Fig.7). Burner burns the fuel to obtain heat and heat exchanger transmits the heat to incoming air. There are two ways to aquire heater: first way is to calculate required parameters for burner and exchanger, buy it separately and assemble, second way is to buy already assembled heater. The main problem with assembling heater is that components are not fitting to each other: mounting holes of the burner and exchanger are often in mismatched places. That means, that construction needs additional reworks. In addition, installation of covering is also required. In case with already assembled heater, it is only necessary to put attention on dimensions of the heater. The main part of choice between two ways is price, which is not so different, since price of separated details plus reworks are equivalent to price of assembled heater. Based on the above, assembled and ready for use heat exchange unit is chosen.

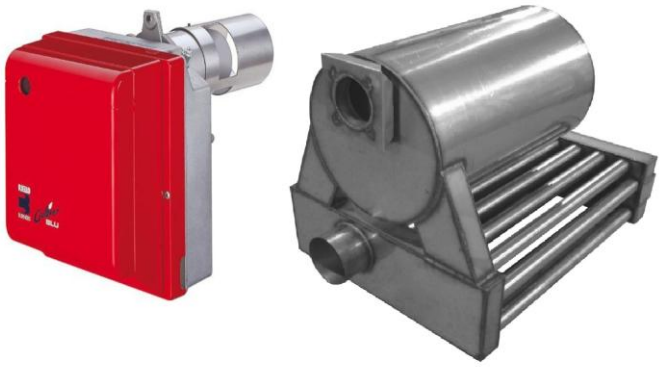


Fig. 7. Burner and heat exchanger for painting chamber [13]

It is pretty much impossible to find a heat exchange module with the same power as calculated is (266,5kW), so the only way is to find it with the closest power value. Three heat exchange modules with the closest power values from different manufacturers are found on the market (Fig.8):

Fig. 8. Heat exchange modules

1) Heatco HE750 [14]

	Power (kW)	Airflow (m^3/h)	Fuel consumption (m^3/h)	Overall dimensions height x length x width (mm)
Heatco HE750	278	17628	9,8	1524 x 1829 x 1173

This type of heater stands out by its power-fuel consumption ratio, but low air transmittance do not allow to achieve required air velocity in painting chamber.

2) Powrmatic HEM Heat Exchange Module [15]

	Power (kW)	Airflow (m^3/h)	Fuel consumption (m^3/h)	Overall dimensions height x length x width (mm)
Powrmatic HEM	200	15012	8,7	1975 x 1750 x 980

It has the lowest fuel consumption, but its air transmittance is too low.

3) Modern-tech MT 8 2017.2.2 [13]

	Power (kW)	Airflow (m^3/h)	Fuel consumption (m^3/h)	Overall dimensions height x length x width (mm)
MT 8 2017.2.2	287	21000	11,4	1414 x 1361 x 1095

This is the only heater, that can pass through required airflow rate, but it has the greatest fuel consumption.

Modern-tech MT 8 2017.2.2 is the only of the proposed, that can pass through required air flow rate. In addition, it has 7,2% power margin, which is important for long-term exploitation.

2.4 Fan capacity

To achieve required air flow in painting chamber, it is necessary to calculate proper fan capacity. It is very important to consider ventilation resistance, which is caused by the duct, filters and heater. To calculate resistance, a sketch of ventilation system needs to be done, to consider length of the duct. Plan of the room and ventilation system is shown below:

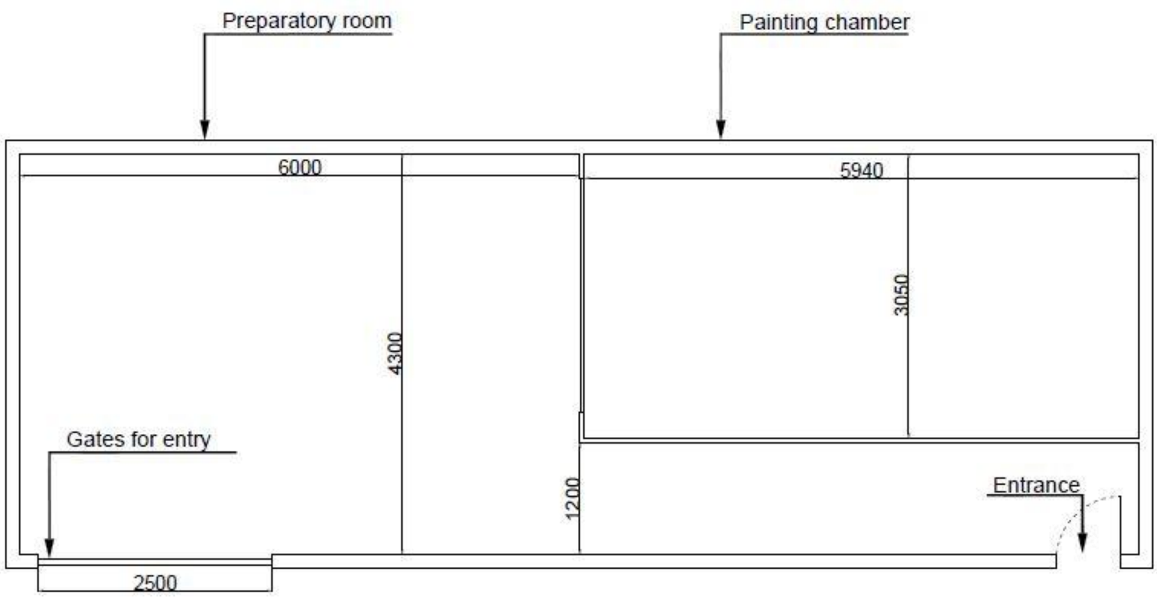


Fig.9. Plan of the workshop

It is very important to install the ventilation system inside of the building. It is necessary to avoid heat losses and moisture formation within the system. Paying attention to the plan, it is clear, that there is no enough space for all required components of ventilation system. It needs to be constructed as compact as it possible. For that purpose, it is necessary to add some technical changes to the plan of workshop. Changes are shown below:

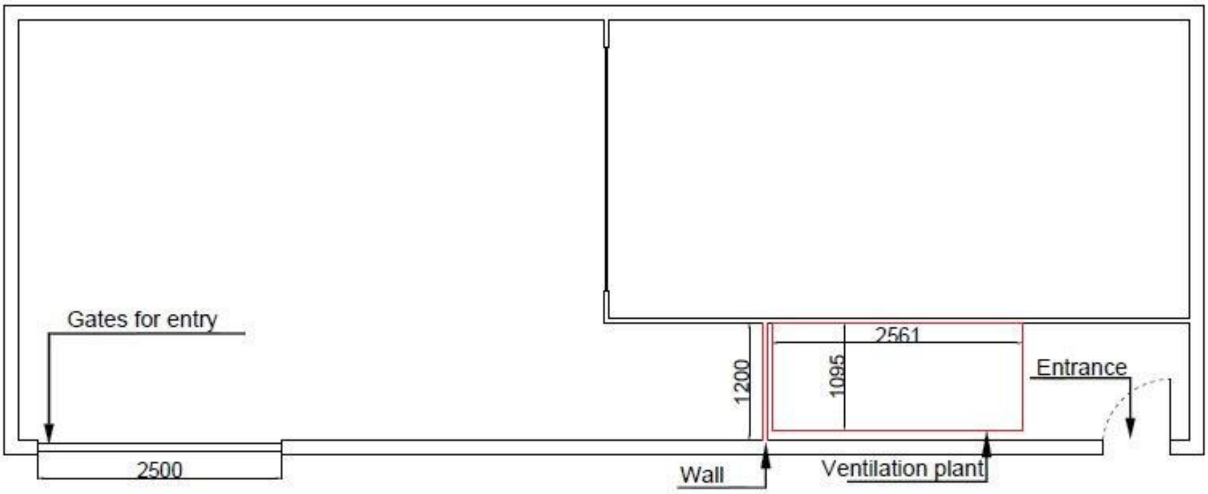


Fig.10. Plan of the workshop with installed ventilation plant

This location of the ventilation plant is chosen on purpose and has many advantages:

1) Air income is provided at the center of the painting chamber, which grants steady ventilation of the whole area

2) Possibility to isolate ventilation plant by the wall to decrease noise level

3) Close location of fans allows to use single valve to regulate air flows.

Now, when location of the ventilation system is chosen, it is possible to create 3D model of the ventilation (Fig.11,Fig.12). It is necessary for air resistance calculation. Air resistance or pressure drop is caused by air speed and all elements of the ventilation. Pressure,developed by the fan have to overcome air resistance, otherwise air motion will not be achieved.

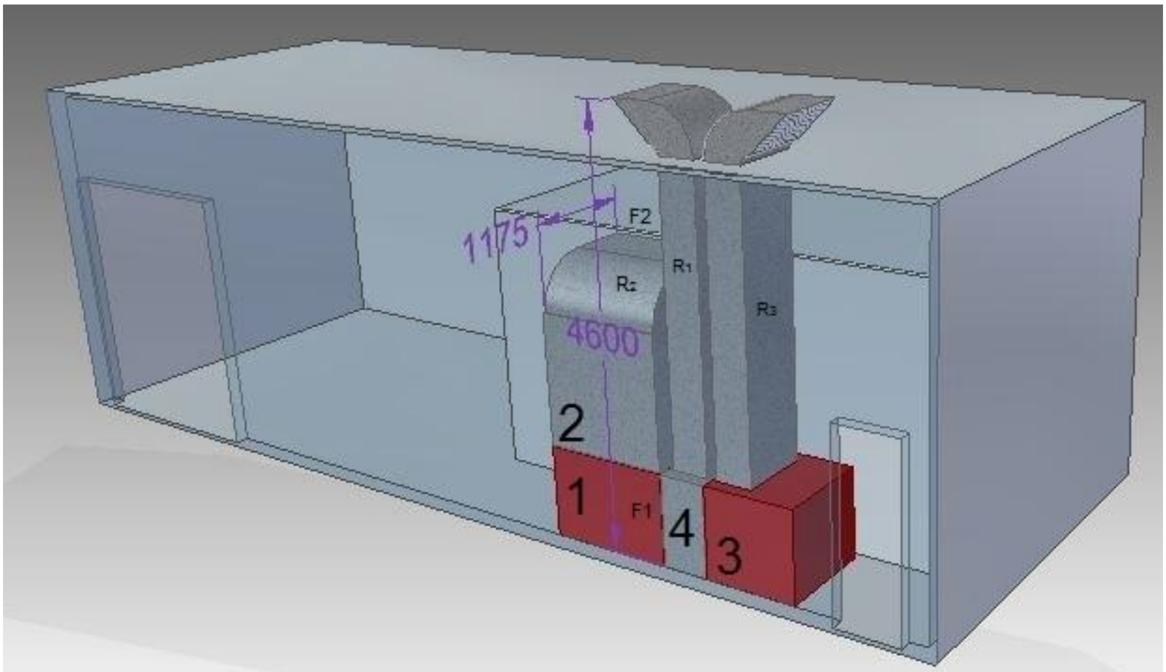


Fig.11. Painting chamber

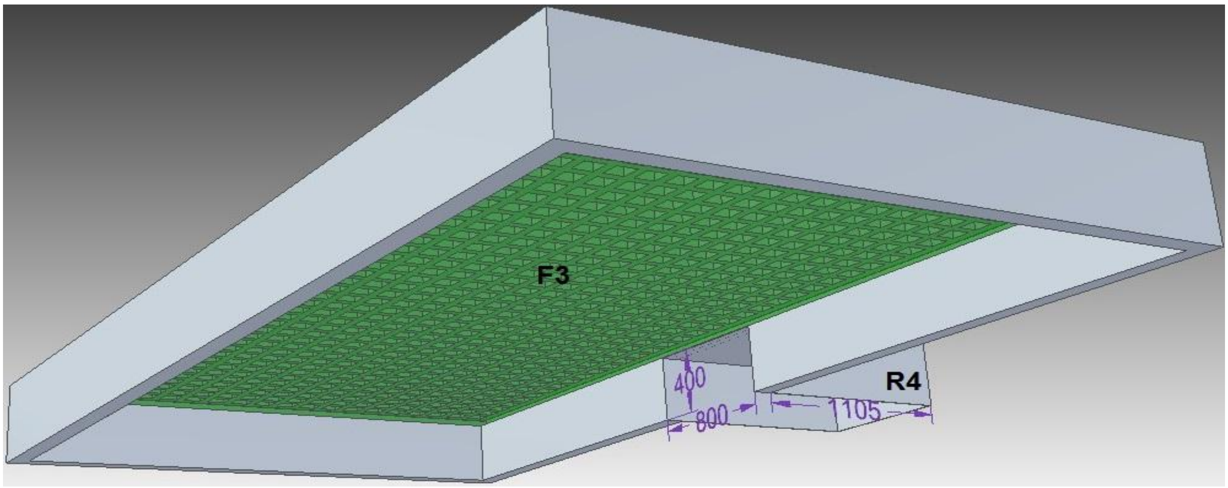


Fig.12. Bottom side of the painting chamber

Where:
1 – supply fan; 2 – heater; 3 – exhaust fan; 4 – regulation valve

R_x – sectors of the duct (required for air resistance calculation)

F_x - filters

Fans are marked red, because its dimensions are conditional and will differ after calculation.

Total air resistance consists of air resistance of the duct, heater and filters. Air resistance of the duct can be calculated using special table:

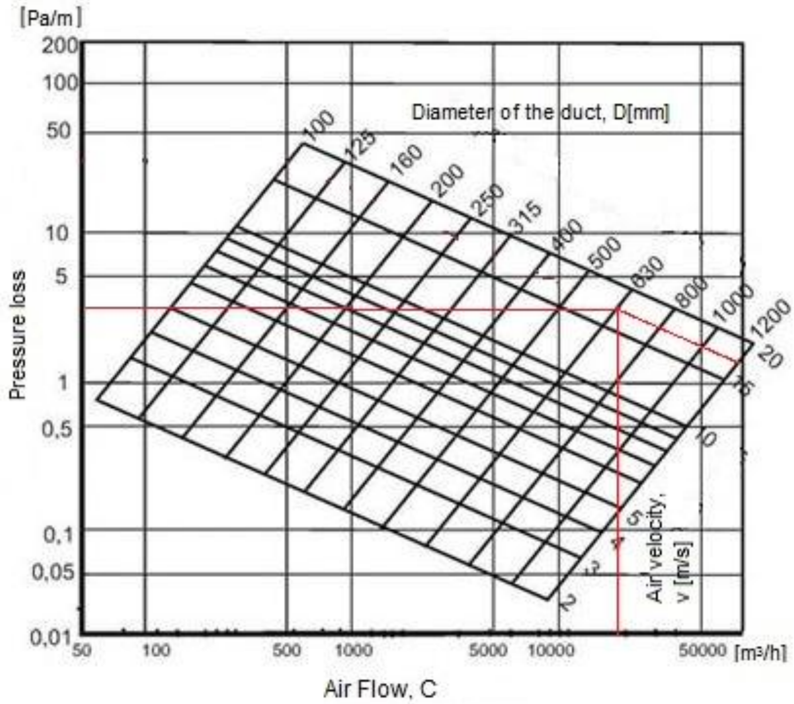


Fig.13. Duct pressure loss [16]

Table shows parameters for the circular duct, but it is allowed to apply it for rectangular duct with the same cross section area. Air resistance of the first sector can be calculated as:

$$R_x = L \times R_l \text{ [17]}$$

Where:

R_x – air resistance of the duct in particular sector [Pa]

L – length of the duct [m] – 4,6 m, obtained from the 3D model of the painting chamber

R_l – pressure loss [Pa/m] – according to the table, it is approximately 4 Pa/m

So air resistance of the first sector (R_1) is:

$$R_1 = 4{,}6 \times 4 = 18{,}4 \text{ Pa}$$

Air resistance of the second sector (R_2) is:

$$R_2 = 1{,}175 \times 4 = 4{,}7 \text{ Pa}$$

Air resistance of the third sector (R_3) is:

$$R_3 = 4{,}6 \times 4 = 18{,}4 \text{ Pa}$$

Air resistance of the fourth sector (R_4) is:

$$R_4 = 1{,}145 \times 4 = 4{,}58 \text{ Pa}$$

And total air resistance of the duct is a summ of all sectors:

$$18{,}4 \times 2 + 4{,}7 + 4{,}58 = 46{,}1 \text{ Pa}$$

Air resistance of the heater can be obtained from the table, introduced by manufacturer in datasheet:

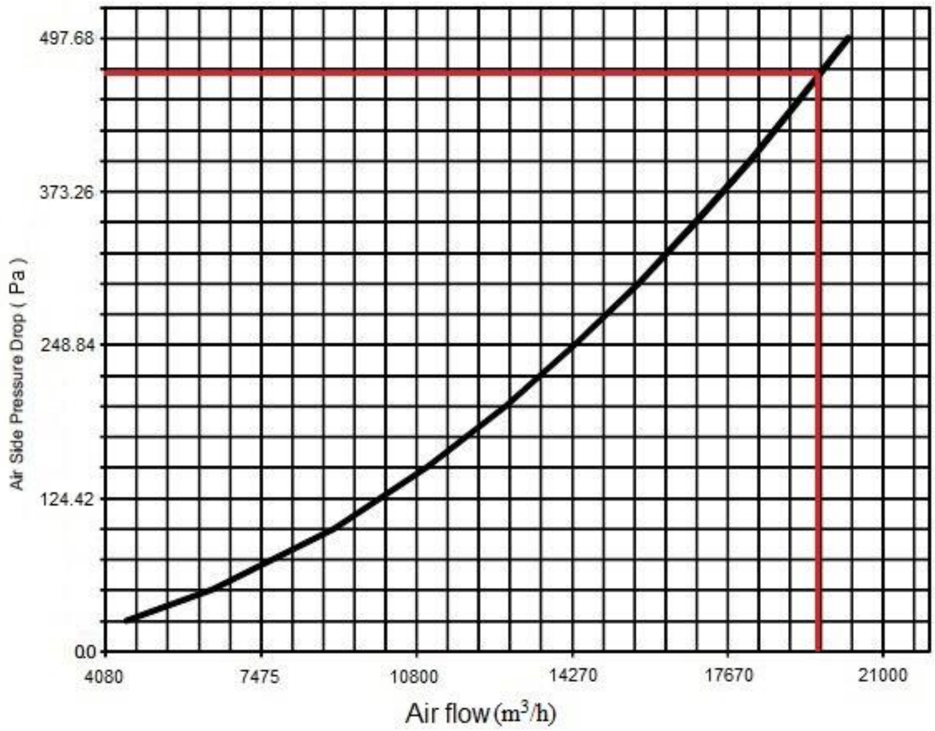


Fig.14. Pressure drop of the heater [14]

Air resistance of the heater is 470 Pa.

Filtration in painting chamber is very important – incoming air has to be cleaned from mechenical parts to prevent its contact with painted sufrace (prefiltration) and also air has to be cleaned from painting vapors to grant smooth painting surface (paint absorbing filtration). For that purposes two types of filters are used: coarse filter and fine filter. Requirements for filters are met by the EN779:2012 standard (Tab.7). Coarse filter class has to match G2-G4, ceiling filter: M5-M6 and paint resistant filter has to match G2-G4, but with paint absorbing properties.

Tab.7. European Air Filter Test Standard EN 779:2012 [18]

Filter Type	New EN779 classification	Average Arrestance (%)	Average Efficiency (%) @ 0,4 µm	Final pressure drop (Pa)	Minimum Efficiency @ 0,4 µm
Coarse Filter	G1 G2 G3 G4	50≤Am<65 65≤Am<80 80≤Am<90 90≤Am		250 250 250 250	
Medium Filter	M5 M6		40≤Em<60 60≤Em<80	450 450	
Fine Filter	F7 F8 F9		80≤Em<90 90≤Em<95 95≤Em	450 450 450	35 55 70

According to EN779:2012, final pressure drop of coarse filter is allowed to 250 Pa and final pressure drop of fine filter is 450 Pa. Designed ventilation system has 3 filters:

F_1 – coarse filter (250 Pa)

F_2 – fine filter (450 Pa)

F_3 – paint filter (250 Pa)

Total pressure drop caused by filters is:

$$450 + 250 \times 2 = 950 \text{ Pa}$$

Now, when air resistance of all components, required for air supply, are found, it is possible to calculate total air resistance:

$$F_{res} + R_{res} + H_{res} = 950 + 470 + 46{,}1 \approx 1466 \text{ Pa}$$

Required output of both fans should be at least 19548 m^3/h and it has to overcome 1466 Pa of air resistance. Now, when all required parameters are calculated, it is possible to choose type of the fans and determine power division between the fans. It is required to achieve necessary pressure in painting chamber.

There are 2 most common types of fans (Fig.15):

1) Axial-flow fan – consist of stator and rotor. Ventilation blades are installed on rotor. Motion of the rotor causes blades to push air forward.

Advantages: simple construction, low cost
Disadvantages: low developed pressure

2) Centrifugal fan – moves air using rotating impellers. Accelerates air radially, changing the direction of the airflow. Due to centrifugal force, those fans are able to achieve high air pressure.

Advantages: high developed pressure
Disadvantages: high cost

Air resistance of the ventilation system is 1466 Pa. Axial-flow fans with required airflow rate are simply not able to overcome that air resistance. That is why centrifugal type fans are used for painting chamber.

Fig.15. Types of fans [19]

There are 3 conditions of pressure in painting chamber:

1) Positive pressure – it is achieved, when supply fan has more capacity than exhaust fan. In this case, air excess is eliminated through gaps in painting chamber, preventing contamination of the painting surface.

2) Neutral pressure – it is achieved, when capacity of both fans is equal. In this case, painting chamber should be well sealed to avoid dust hitting on the painting surface.

3) Negative pressure – when exhaust fan has more capacity than supply fan. In this case, elimination of paint vapors is the most effective, however, painting chamber should be perfectly sealed to prevent suction of the dust and insects inside.

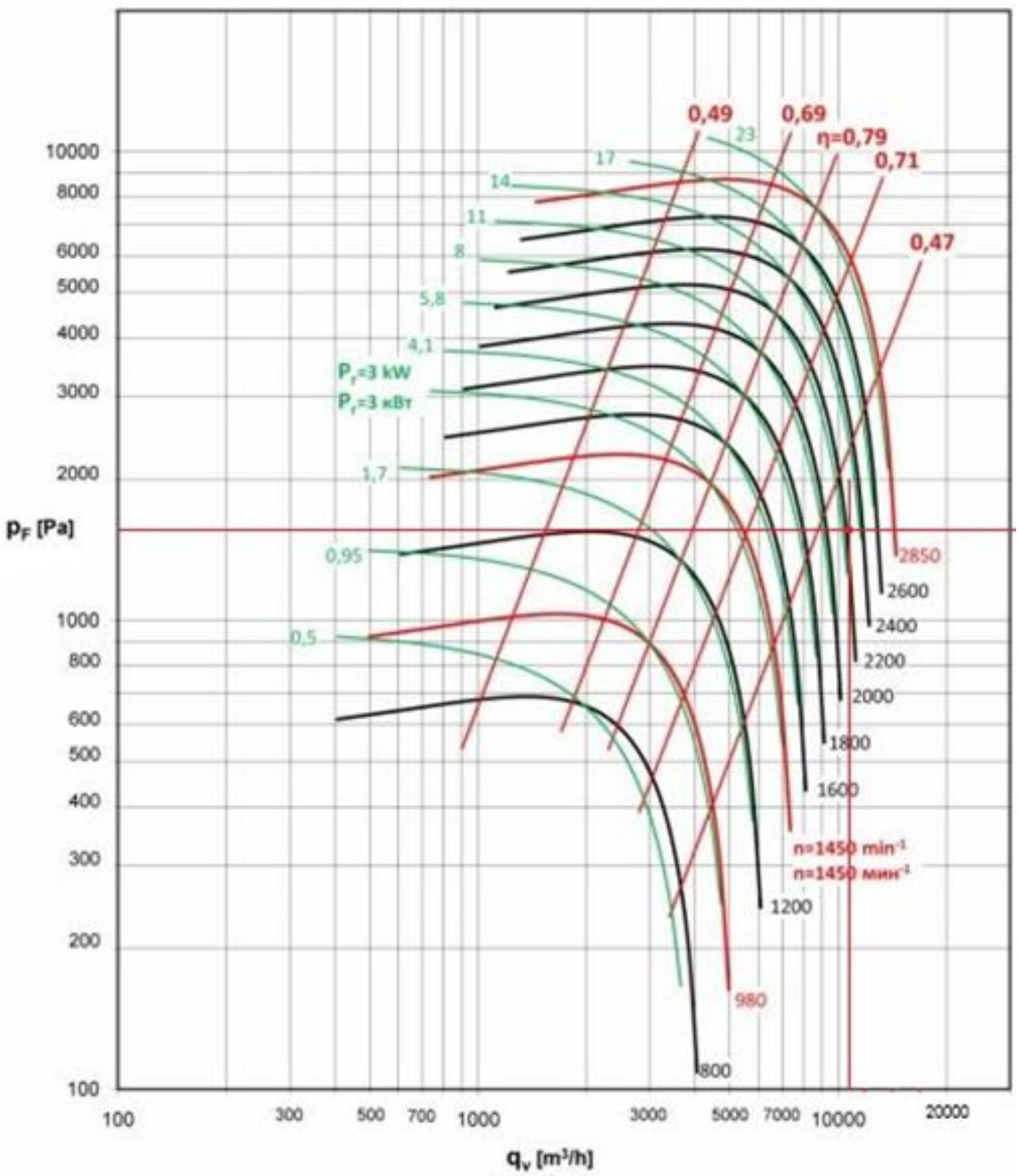
Since ventilation system is meant for already existing painting chamber, it is quite difficult and expensive to achieve its sealing. However, painting chamber with positive pressure grants „clean room" by blowing dust away through the gaps and there is no need in sealing. To achieve „clean room" effect, performance of the supply fan should be 10-15% greater than performance of the exhaust fan. For proper choice of fans, detailed datasheet is required. Variety of the fans on the market is high, however, fans with the most accurate parameters and suitable datasheet are offered by „Izoteh" and „Elektror" companies.

Performance ratio for supply fan (55%-57.5%) : 10751 m^3/h – 11240 m^3/h

Performance ratio for exhaust fan (45%-42.5%) : 8797 m^3/h – 8308 m^3/h

First is introduced conjunction of the „Izoteh“ fans:

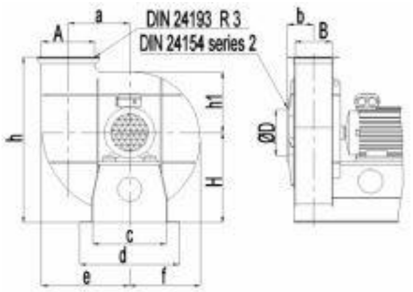
a) Supply fan – **ROT1-756-86-28-70**



Model	Nominal rotation speed $(\frac{1}{min})$	Power (kW)	Noise (dB)
ROT1-756-86-28-70	2850	23	104

Fig.16. Characteristics of the fan ROT1-756-86-28-70 [20]

Dimensions:



Fan type	a	b	c	d	e	f	g	h
ROT1-756-86-28-70	434.5	181	500	640	628	489	414	1070

Fig.17. Dimensions of the fan ROT1-756-86-28-70 [20]

With ventilation resistance of 1466 Pa, performance of the supply fan is about 11000 m^3/h, which is 56,3% of all required airflow. Those parameters are achieved on 2200 $\frac{1}{\min}$ with motor power of 11 kW. Overall dimensions of the fan are (1070x1117) mm, width of the installation place is 1200 mm, so there is dimensional reserve for installation.

b) Exhaust fan – **ROT2-574-50-28-62**

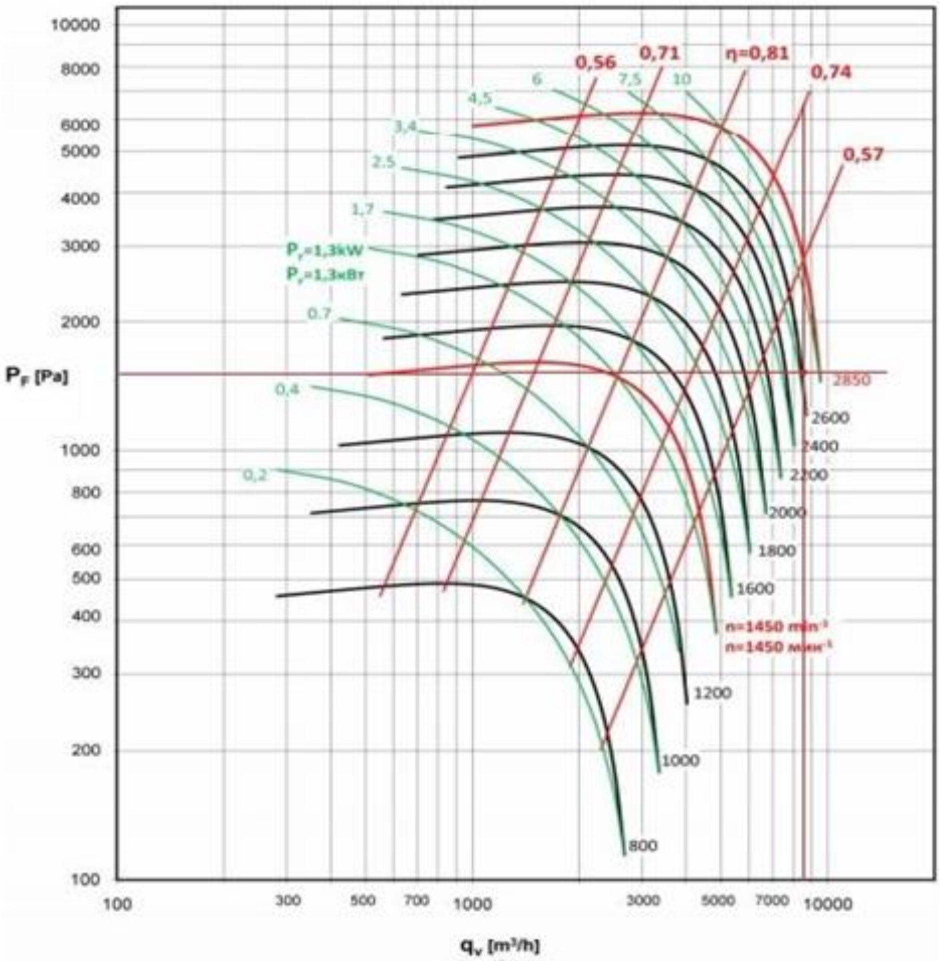
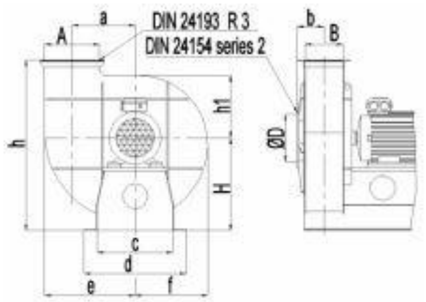


Fig.18. Characteristics of the fan ROT2-574-50-28-62 [20]

Model	Nominal rotation speed $(\frac{1}{min})$	Power (kW)	Noise (dB)
ROT2-574-50-28-62	2850	10	100

Dimensions:



Fan type	a	b	c	d	e	f	g	h
ROT2-574-50-28-62	434	158	450	610	539	434	116	1012

Fig.19. Dimensions of the fan ROT2-574-50-28-62 [20]

With ventilation resistance of 1466 Pa, performance of the exhaust fan is about 8600 m^3/h, which is 44% of all required airflow. Those parameters are achieved on 2600 $\frac{1}{min}$ with motor power of 7,5 kW. Overall dimensions of the fan are (1012x973) mm, width of the installation place is 1200 mm, so there is dimensional reserve for installation.

Total developed airflowrate is 19600 m^3/h , which is 100,3%. On rated power, achieved airflow rate is about 23500 m^3/h. Power margin is 20%.

Second is introduced conjunction of the „Elektror“ fans:

a) Supply fan – **CFL 450**

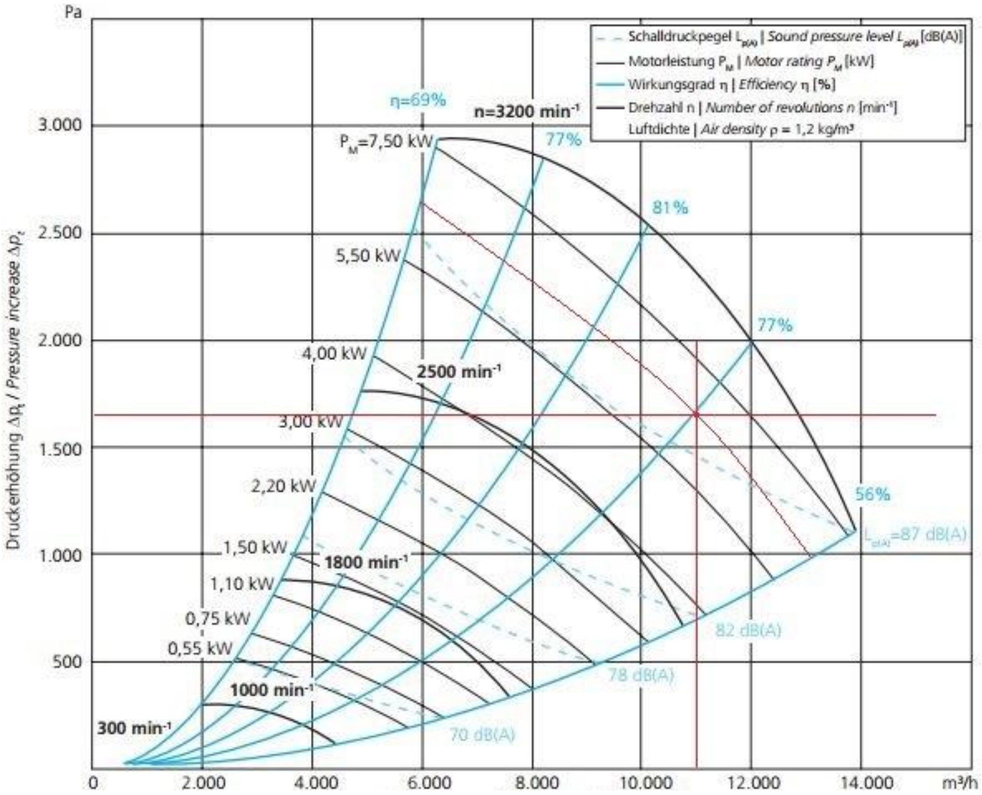
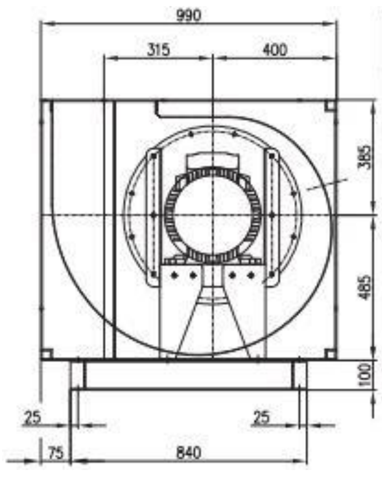


Fig.20. Characteristics of the fan CFL 450 [21]

Dimensions:



Motorbaugröße | *Motor size*	132 S/2
Motorleistung P_M | *Motor rating P_M* [kW]	7,50
Gewicht | *Weight* [kg]	179
L [mm]	800

Fig.21. Dimensions of the fan CFL 450 [21]

With ventilation resistance of 1466 Pa, performance of the supply fan is about 11000 m^3/h, which is 56,3% of all required airflow. Those parameters are achieved on 2900 $\frac{1}{\mathrm{min}}$ with motor power of 6,7 kW. Overall dimensions of the fan are (990x970) mm, width of the installation place is 1200 mm, so there is dimensional reserve for installation.

b) Exhaust fan – **CFL 400**

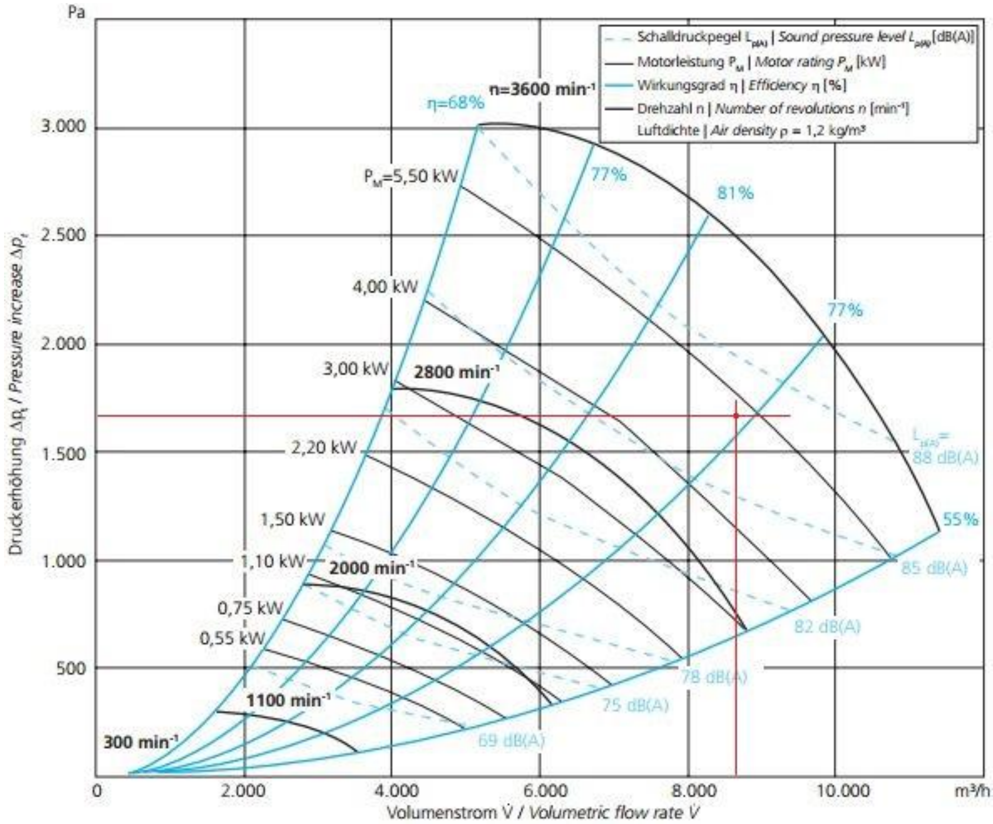
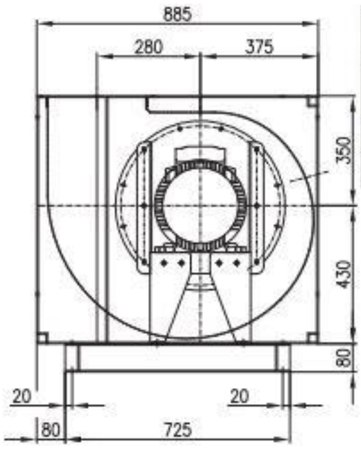


Fig.22. Characteristics of the fan CFL 400 [21]

Dimensions:



Motorbaugröße | *Motor size*	132 S/2
Motorleistung P_M | *Motor rating P_M* [kW]	5,50
Gewicht | *Weight* [kg]	139
L [mm]	780

Fig.23. Dimensions of the fan CFL 400 [21]

With ventilation resistance of 1466 Pa, performance of the supply fan is about 8600 m^3/h, which is 44% of all required airflow. Those parameters are achieved on 3200 $\frac{1}{\min}$ with motor power of 5,4 kW. Overall dimensions of the fan are (885x860) mm, width of the installation place is 1200 mm, so there is dimensional reserve for installation.

Total developed airflowrate is 19600 m^3/h , which is 100,3%. On rated power, achieved airflow rate is about 24000 m^3/h. Power margin is 22,3%.

In comparison of both conjunctions, it is seen, that with equal results, fans of „Elektror“ require less power, have smaller dimensions, lighter and produce less noise, than fans of „Izoteh“. Basing on above, fans of „Elektror“ company are chosen for painting chamber.

2.5 Air flow regulation

Regulation of air flows in painting chamber is important. It allows to put painting chamber in different working modes – spray mode or bake mode by regulating mixes of intake and outtake air flows.

Spray mode – process, when paint is sprayed on surface. Spray mode is meant for a high-volume of low-temperature ventilation. It grants great quality for painted surface and effectively eliminates paint vapors. Required conditions in that mode are: providing of 100% outside air that is tempered to (20-22) ºC. [5]

Bake mode – process for fast paint drying. Bake mode is meant for high-temperature ventilation. Required temperature in that mode is (60-70) ºC. To reach that temperature, recirculation of air is applied in range 80-90 % of all air flow circulation. Other 10-20 % of air is taken from outside to provide elimination of moisture and vapors. [5]

To provide ventilation with regulation abilities, in painting chamber are spread next solutions:

1) Regulation with one common valve – 4-way junction duct with regulation valve at the center (Fig.24).

Advantages: easy regulation, one valve regulates all air flows

Disadvantages: in bake mode, only supply fan works and that leads to low air flow rate in painting chamber

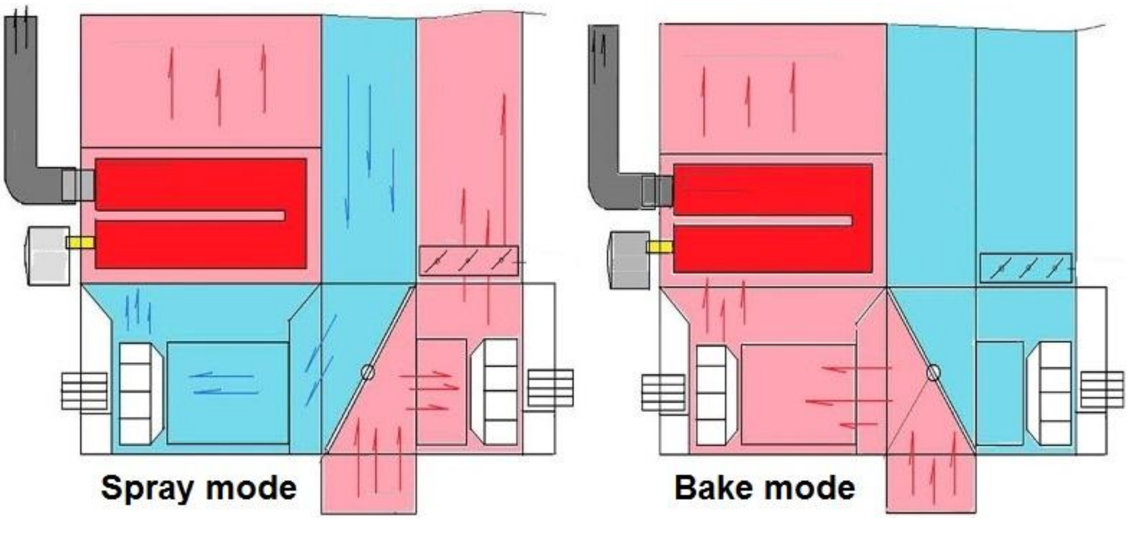


Fig.24. Regulation with one common valve [22]

2) Regulation with 3 valves – to control air flows, 3 one-direction valves are used (Fig.25)

Advantages: in bake mode, 2 fans are in work

Disadvantages: 3 valves should be automated instead of one

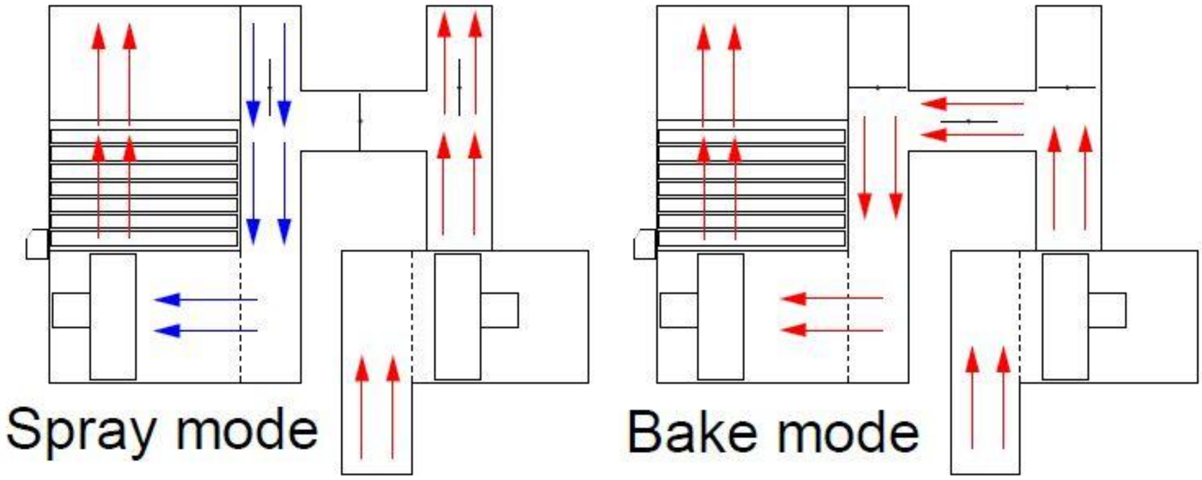


Fig.25. Regulation with 3 valves

To choose, what solution to use, 2 important aspects are considered. First of all, using first solution, it is impossible to have high air flow rate in painting chamber during bake mode. Secondly, 4-way junction duct with regulation valve is rarely used and it is very hard to find it on the market. Second solution allows regulate air flow with high accuracy, one-direction valves are widespread and easy to find. So, second type of regulation fits better for required task and will be used in this ventilation system.

One-direction ventilation valves are possible to obtain from local (Estonian) distributors – "Systemair" and "Lindab".

1) Systemair SRK 80-50

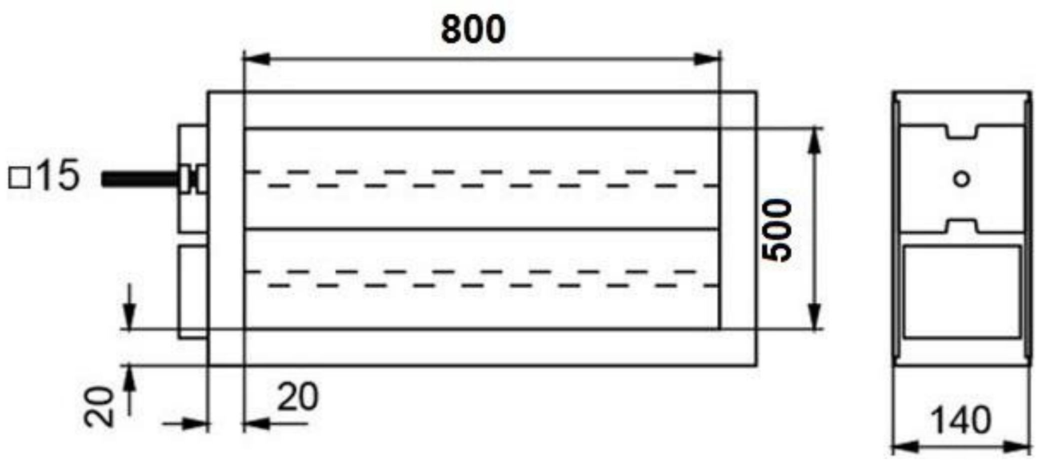


Fig.26. Dimensions of SRK 80-50 [23]

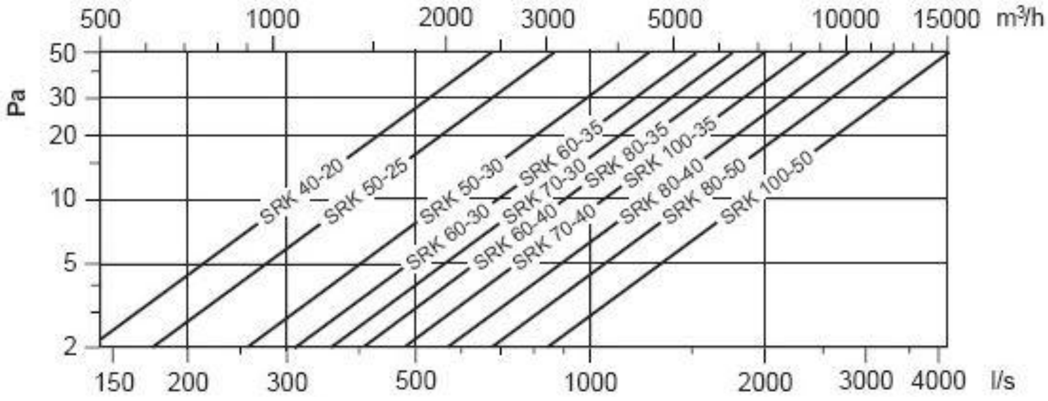


Fig.27. Parameters of SRK 80-50 [23]

1) Lindab JSMMU

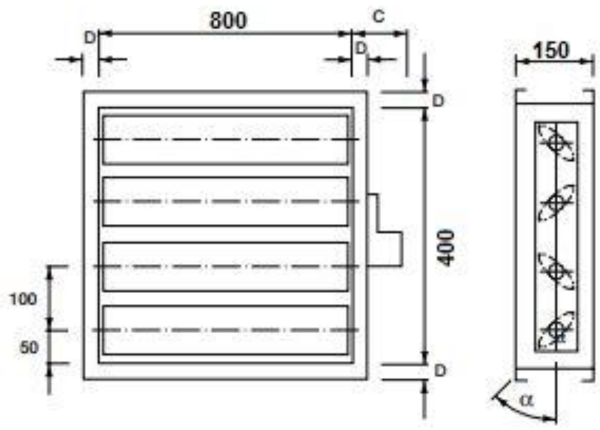


Fig.28. Dimensions of JSMMU [24]

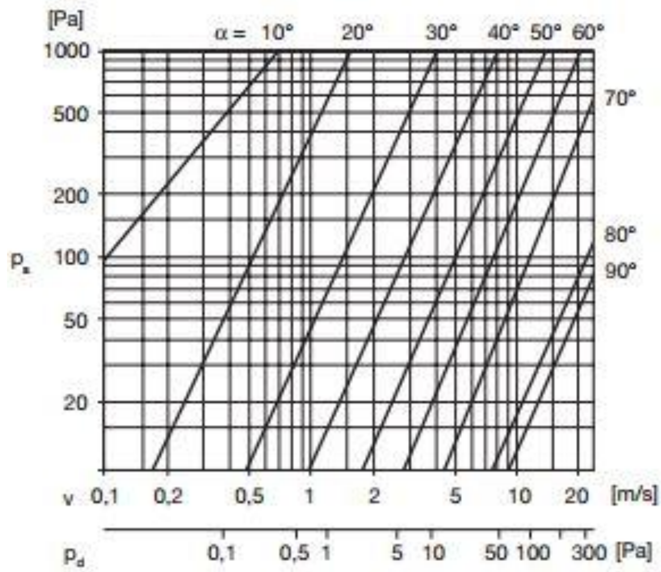


Fig.29. Parameters of JSMMU [24]

In favor of “Lindab” valve, it has slightly lower pressure drop, than “Systemair” valve. Moreover, “Lindab” valve has absolutely the same sizes as calculated duct is, so there is no need in adapters. “Lindab” valve fits better for required task and will be used in this ventilation system.

2.6 3D model

All necessary calculations are made, dimensions of the key devices are obtained. Now, it is possible to create 3D model of the ventilation, using all proper dimensions. 3D model is necessary to gain vision of the whole construction. It allows to detect weak spots or specific features, that need to be changed or replaced. In modern designing, creation of the 3D models has an important role.

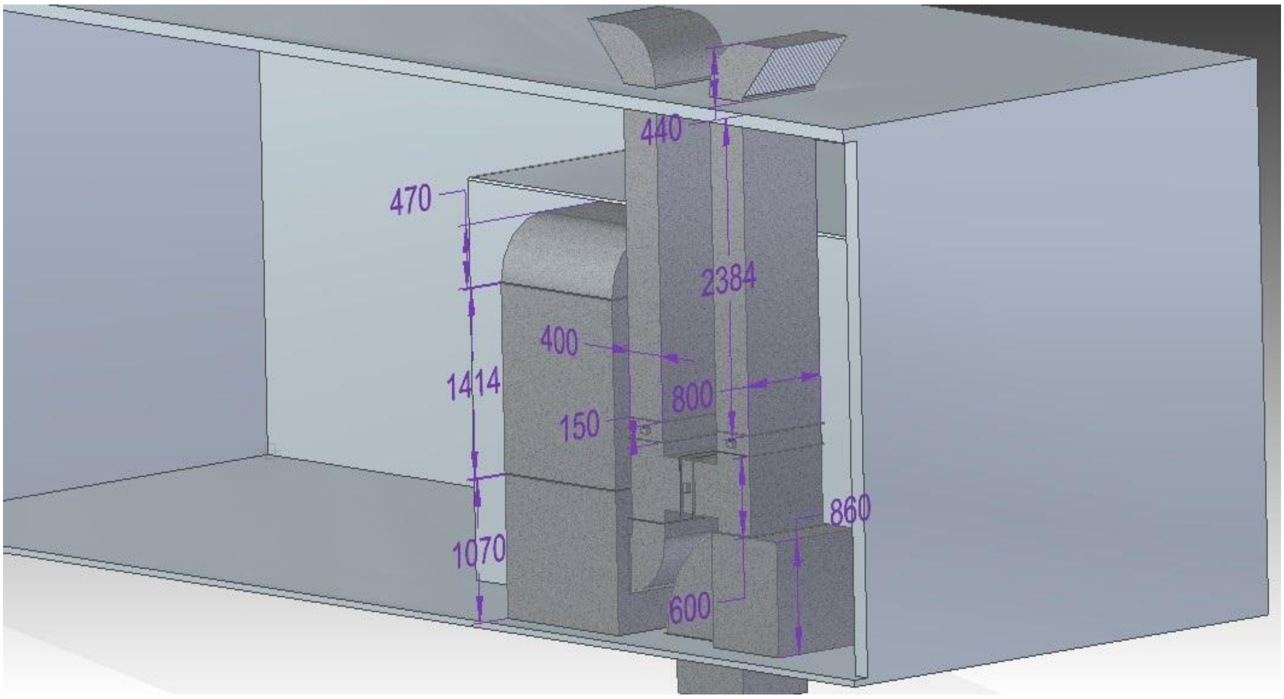
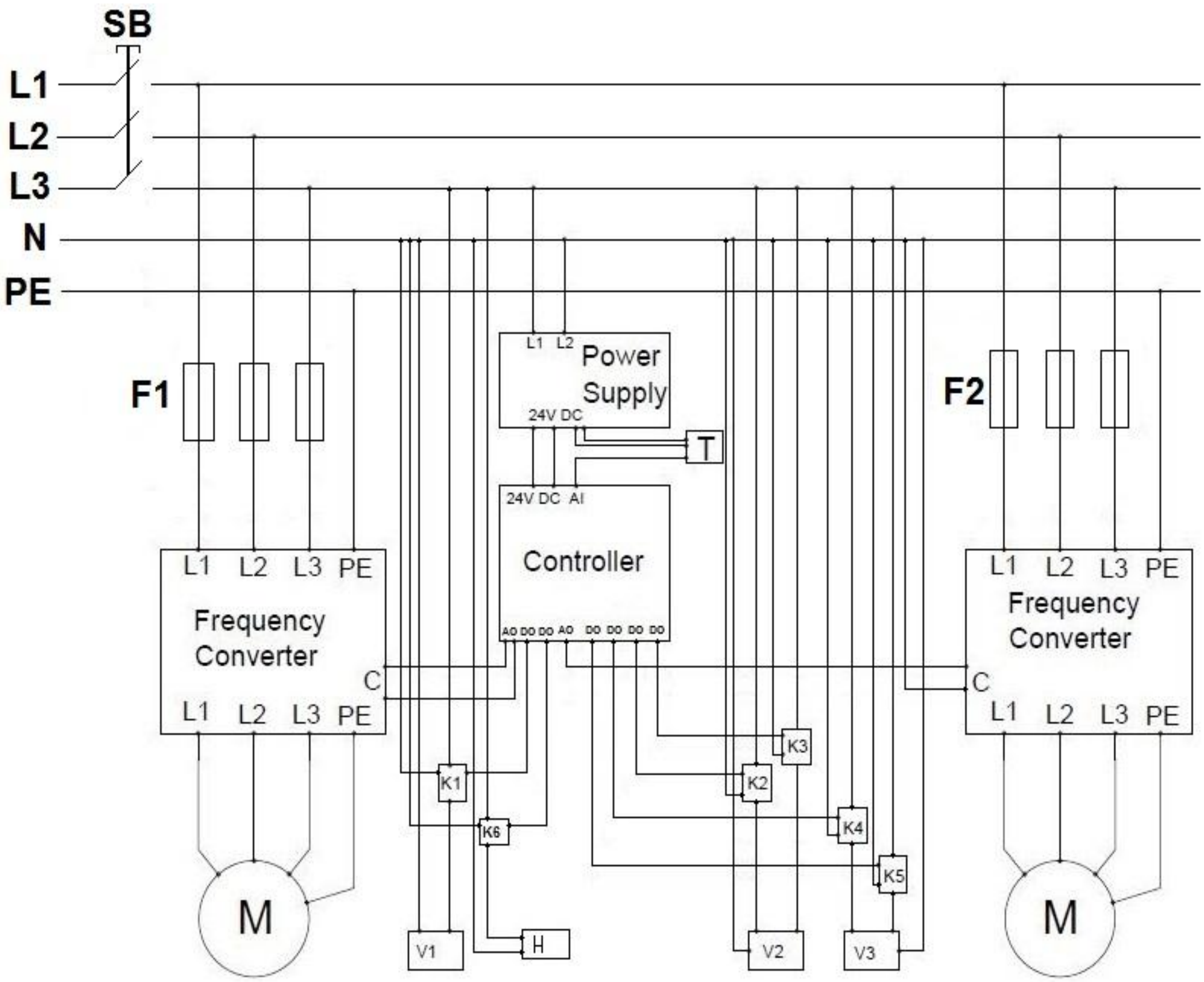


Fig.30. 3D model of the ventilation system

3. Automation

3.1 Purpose and wiring diagram

For qualitative painting, lots of parameters should be precisely regulated: air velocity, temperature inside the chamber, working mode of the ventilation. For comfortable control of all these parameters, automation is required - the use of various control systems for operating equipment. To automate ventilation, devices such as PLC controller, frequency converter and temperature sensor are used. Basing on above, wiring diagram is created:



L	Phase	C	Control signal
N	Neutral	F	Fuse
PE	Ground	AI	Analog input
M	3 Phase Motor	AO	Analog output
K	Relay	DO	Discrete output
T	Temperature sensor	V	Ventilation Valve
H	Heater	SB	Push-button switch

Fig.31. Wiring diagram for ventilation system control

3.2 Frequency converter

Frequency converter - electronic device to regulate voltage frequency. It allows to start motor smoothly and regulate rotation speed. In painting chamber it is necessary to regulate air velocity and pressure. All of it is possible by regulating motor rotation speed of the supply or exhaust fan. To choose correct frequency converter, it is important to consider motor parameters (power, rated current) and possibility to control it through the controller.

Tab.8. Actuator parameters [21]

Supply fan		Exhaust fan	
Three-phase asynchronous motor		Three-phase asynchronous motor	
Voltage	380 V	Voltage	380 V
Power	7,5 kW	Power	5,5 kW
Rated current	15,02 A	Rated current	11,42 A

Variety of the frequency converters on the market is high, but worthy of attention are „ABB“ and „Schneider“ frequency converters, because those are approved as a reliable products and available on estonian market.

a) „ABB“ frequency converters:

ACS310-03E-17A2-4 – frequency converter for actuator of the supply fan. It corresponds to all required parameters and there is possibility to control it using (0-10) V analog input.

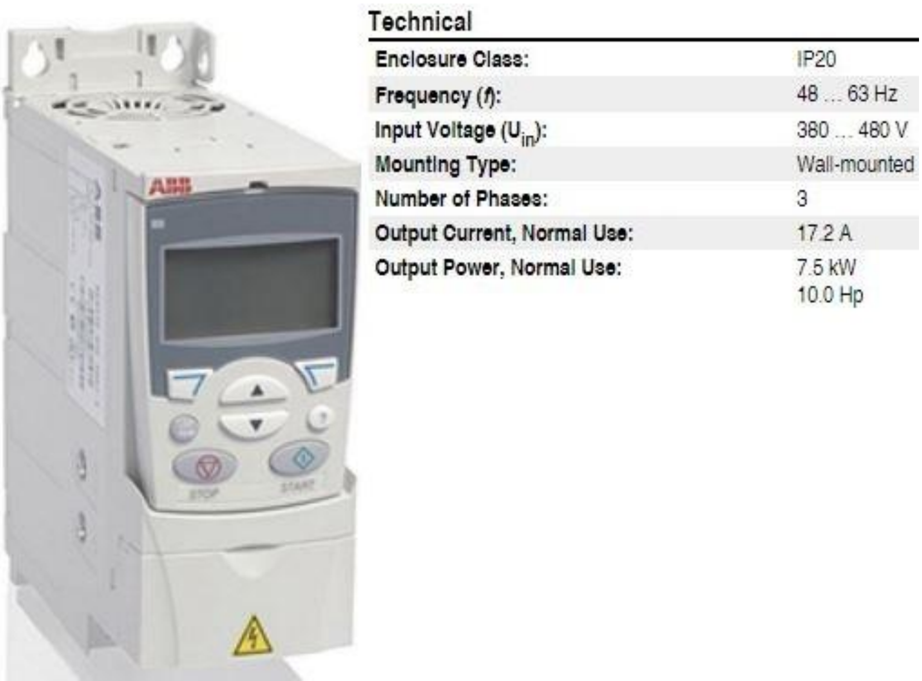


Fig.32. ACS310-03E-17A2-4 [25]

ACS310-03E-13A8-4 - frequency converter for actuator of the exhaust fan. It corresponds to all required parameters and there is possibility to control it using (0-10) V analog input.

Technical

Enclosure Class:	IP20
Frequency (*f*):	48 … 63 Hz
Input Voltage (U_{in}):	380 … 480 V
Mounting Type:	Wall-mounted
Number of Phases:	3
Output Current, Normal Use:	13.8 A
Output Power, Normal Use:	5.5 kW 7.5 Hp

Fig.33. ACS310-03E-13A8-4 [26]

b) „Schneider“ frequency converters:

ATV312HU75N4 - frequency converter for actuator of the supply fan. It corresponds to all required parameters and there is possibility to control it using (0-10) V or (0-20) mA analog input.

Motor		Line supply (input)					Drive (output)	
Power indicated on plate (1)		Max. current line (2)		Apparent power	Max. inrush current (3)	Power dissipated at nominal current	Nominal current (1)	Max. transient current (1) (4)
		at 380 V	at 500 V					
kW	HP	A	A	kVA	A	W	A	A
7.5	10	27.7	21.0	18.0	30	269	17.0	25.5

Fig.34. ATV312HU75N4 [27]

ATV312HU55N4 - frequency converter for actuator of the exhaust fan. It corresponds to all required parameters and there is possibility to control it using (0-10) V or (0-20) mA analog input.

Motor		Line supply (input)					Drive (output)	
Power indicated on plate (1)		Max. current line (2)		Apparent power	Max. inrush current (3)	Power dissipated at nominal current	Nominal current (1)	Max. transient current (1) (4)
		at 380 V	at 500 V					
kW	HP	A	A	kVA	A	W	A	A
5.5	7.5	21.9	16.5	15.0	30	232	14.3	21.5

Fig.35. ATV312HU55N4 [28]

Both, „Schneider“ and „ABB“ frequency converters have required parameters. „ABB“ offers more compact device and slightly lower price, „Schneider“ offers additional analog input - (0-20) mA. In some situations, input (0-20) mA may be critical advantage, but not in this case, so more compact and cheaper frequency converters of „ABB“ are chosen.

<u>3.3 Regulation valves</u>

Air intake valve and air outtake valve requires 3 positions of the damper: close position, open position and half-close position (80% of the air is recirculated and 20% of the air is taken in). Recirculation valve requires only 2 positions: close position and open position.

Regulation valves „JSMMU“ are controlled by „Belimo LM230A-F“ actuators (Fig.39). Actuator supply voltage is 220 V, so there is no need in voltage adapters. This actuator allows to establish open/close control or 3-point control.

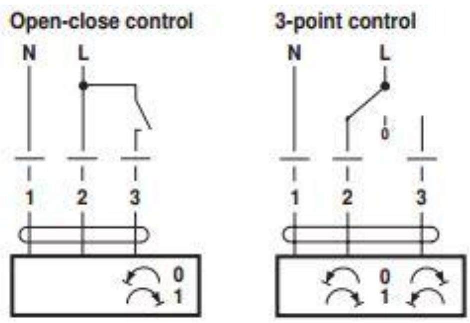


Fig.36. Open/Close control and 3-point control [29]

To control actuator through the controller, realys - an electrically operated switches, are used. 1 relay for recirculation valve (V1), 2 relays for intake valve (V2) and 2 relays for outtake valve (V3). Discrete signal, sent from the controller (24 VDC) to relay, closes supply chain (220 VAC) of the damper actuator and damper takes required position. Control scheme is shown below:

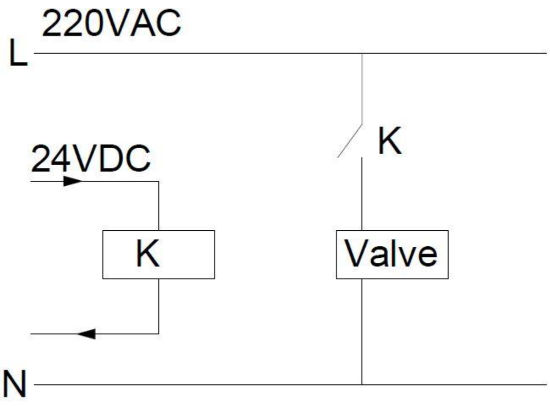


Fig.37. Control of the regulation valve

Scheme shows, that relay work voltage is 24VDC and commutation voltage is 220VAC. Relays with necessary parameters are commonly used in electronics, for example - PE014024:

switching capacity:	5A / 250VAC
type of coil:	Sensibel
coil power:	200 mW
coil voltage:	24 VDC

Fig.38. PE014024 [30]

Nominal voltage		AC 100 ... 240 V, 50/60 Hz
Nominal voltage range		AC 85 ... 265 V
Power consumption	In operation	1.5 W @ nominal torque
	At rest	0.4 W
	For wire sizing	3.5 VA
Connection		Cable 1 m, 3 x 0.75 mm²
Torque (nominal torque)		Min. 5 Nm @ nominal voltage

Fig.39. „Belimo LM230A-F“ actuator [29]

3.4 Temperature sensor

Temperature sensor is required to control air heater. Sensor converts temperature into electric signal and transfers it to the controller. Sensor has 3 connection nests: 2 of them for power supply and 1 is analog output (0-10) V. Wiring diagram is shown below:

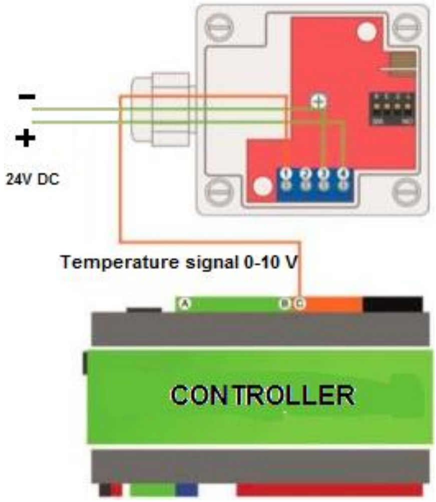


Fig.40. Temperature sensor connection to the controller [31]

Scheme shows, that supply voltage is 24VDC and control signal is (0-10) V. Temperature sensors with necessary parameters are spread in electronics, for example – ATM2-U:

supply voltage	24V AC/DC
temperature range	-30 - +70 °C
output signal	0-10 V

Fig.41. Temperature sensor ATM2-U [32]

3.5 Heater

Heat exchanger „MT 8 2017.2.2“ is equipped with burner „Lamborghini EM 35-E“. This is one step burner. It means, that it has two states: 0 – the burner is turned off and 1 – working state. Using temperature sensor and controller, it is very convinient to control this type of burner: controller keeps the burner working, till required temperature is achieved. After tempersture is achieved, controller turns the signal off and maintains temperture by switching signal on again, if the temperature slightly falls down. Signal and temperature dependence is shown below:

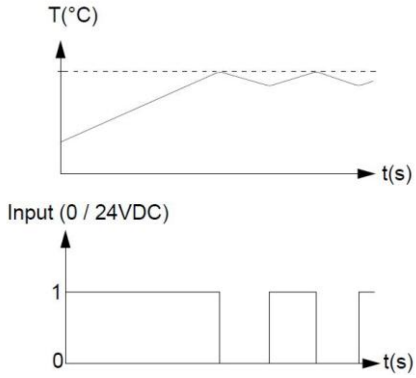


Fig.42. Signal and temperature dependence

„Lamborghini EM 35-E“ supply voltage is 220 V. To controll burner through the controller, the same relay, as for valves is used. Wiring diagram of the EM 35- E is shown below:

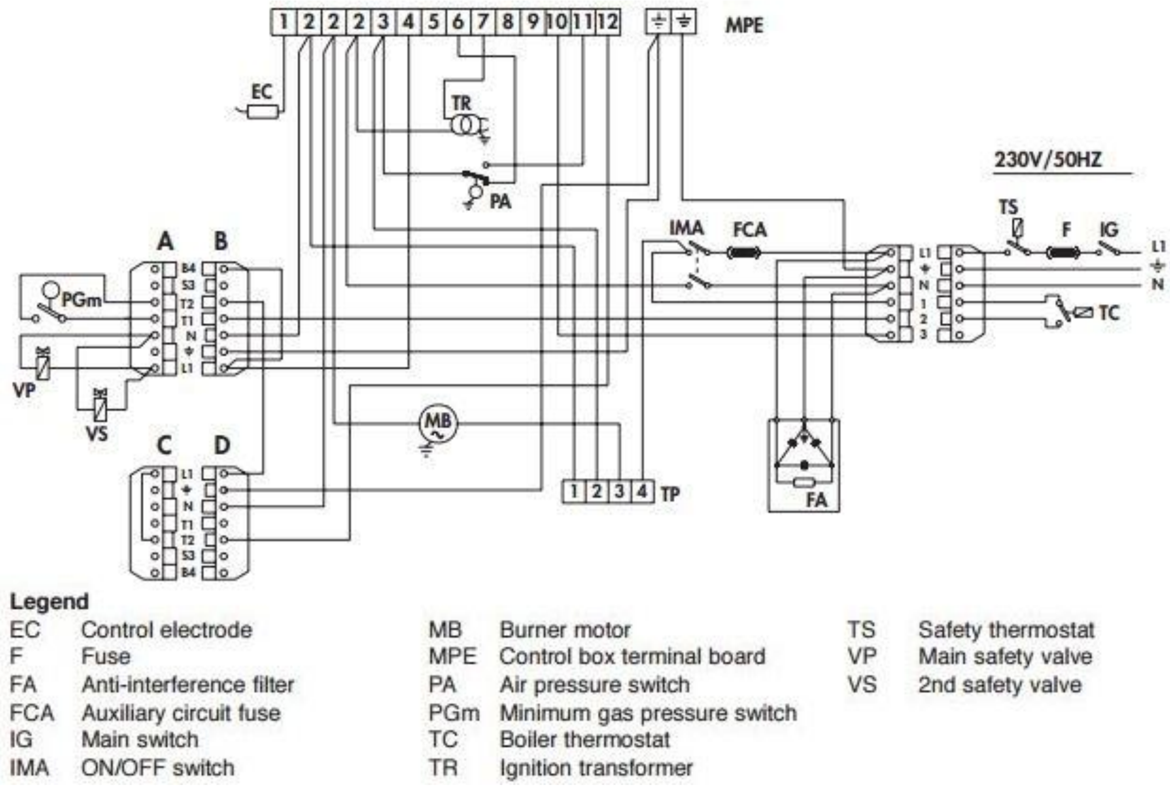


Fig.43. Wiring diagram of the EM 35-E [33]

3.6 Power supply adapter

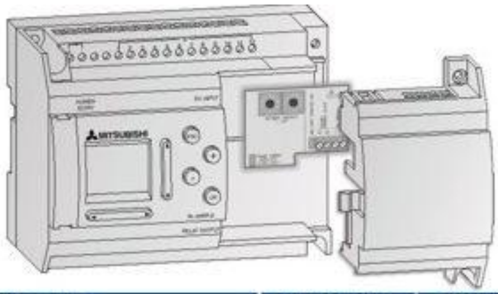
It is not possible to supply every device in wiring diagramm with 220V AC. Devices such as temperature sensor and controller require 24V DC. For that purpose special power adapter is required. Necessary parameters are common in electronics, so there is a big amount of required adapters on the market. For example, adapter „Mean Well DR-45-24“ responds to given parameters and also can be installed on DIN rail.

MODEL		DR-4524
OUTPUT	DC VOLTAGE	24V
	RATED CURRENT	2A
	CURRENT RANGE	0 ~ 2A
	RATED POWER	48W
	RIPPLE & NOISE (max.) Note.2	480mVp-p
	VOLTAGE ADJ. RANGE	21.6 ~ 26.4V
	VOLTAGE TOLERANCE Note.3	±1.0%
	LINE REGULATION	±1.0%
	LOAD REGULATION	±1.0%
	SETUP, RISE TIME	800ms, 60ms/230VAC at full load
	HOLD UP TIME (Typ.)	60ms/230VAC at full load
INPUT	VOLTAGE RANGE	85 ~ 264VAC 120 ~ 370VDC
	FREQUENCY RANGE	47 ~ 63Hz
	EFFICIENCY (Typ.)	72%
	AC CURRENT (Typ.)	1.5A/115VAC 0.75A/230VAC
	INRUSH CURRENT (Typ.)	COLD START 28A/115VAC 56A/230VAC
	LEAKAGE CURRENT	<1mA / 240VAC

Fig.44. Mean Well DR-45-24 [34]

3.7 Controller

Controller is an electronics control unit. In current electric scheme, it responds for temperature control, painting mode and air velocity. As a main control unit, it should be easy to use and understandable for workers. This is the reason to use PLC (programmable logic controller). PLC is a digital computer used for automation of typically industrial electromechanical processes, such as control of machinery on factory assembly lines, amusement rides, or light fixtures. PLCs are designed for multiple arrangements of digital and analog inputs and outputs, extended temperature ranges, immunity to electrical noise, and resistance to vibration and impact [35]. There are a wide range of PLCs on the market. The most common PLCs on estonian market are: „Siemens Simatic“, „Mitsubishi Alpha“ and „Unitronics“. For this current task, controller „Mitsubishi Alpha 2“ (Fig.45) is used, because it supports (0-10) V analog inputs and outputs, has intuitive interface, its software allows to simulate program even without the controller and there is possibility to obtain required software as a student edition to create and simulate program to complete the task.



Base units	AL2-10MR-D	AL2-10MR-A	AL2-14MR-D	AL2-14MR-A	AL2-24MR-D	AL2-24MR-A
I/Os	10		14, expandable to 18		24, expandable to 28	
Power supply	24 V DC	100 – 240 V AC	24 V DC	100 – 240 V AC	24 V DC	100 – 240 V AC
Digital inputs	6		8		15	
Digital inputs with analog capability (0–10V, 9bit)	6	Not applicable	8	Not applicable	8	Not applicable
Relay outputs	4		6		9	
Constant outputs	8 A		8 A		8 A (4x)/2 A (5x)	
Function blocks	Max. 200		Max. 200		Max. 200	
Dimensions (W x H x D) in mm	71.2 x 90 x 52		124.6 x 90 x 52		124.6 x 90 x 52	
Expansion modules for ALPHA 2						
AL2-4EX*	4 dig. inputs (24 V DC) with 2 selectable high-speed counters (1 kHz)					
AL2-4EX-A2*	4 dig. inputs (240 V AC)					
AL2-4EYT*	4 transistor outputs (1A)					
AL2-4EYR*	4 relay outputs (2 A)					
AL2-2DA*	2 analog outputs (0 – 10 V / 4 – 20 mA)					
AL2-2PT-ADP	2 Pt100 temperature converters					
AL2-2TC-ADP	2 K-type thermocouple converters					

Fig.45. Mitsubishi Alpha 2 [36]

Basing on wiring diagram (Fig.31), it is clear, that 1 analog input, 6 discrete outputs and 2 analog outputs are required. On the table above, controller model with necessary parameters is marked with red rectangle. To use analog outputs, expansion module „AL2-2DA“ is required.

3.8 Block scheme and controller program

To perform required tasks using controller „Mitsubishi Alpha 2“ , special software, called „AL-PCS/WIN-E“ is used. It is possible to obtain this software in demo version from company official website [37]. The only difference between demo version and full version is that in demo version no communication function with the controller, but still, there is possibility to simulate created program.

Required tasks for the controller are:

1) Regulation of the temperature in painting chamber by control of the heater using temperature sensor.

2) Choice of the work mode (spray mode or bake mode) by regulating valves.

3) Regulation of the air velocity by regulating motor speed of the fans using frequency converters.

For better understanding of the task, it is necessary to create a block scheme of the painting process. The scheme describes painting procedure step by step. It allows to determine exact tasks of the PLC and create correct program. Block scheme is introduced below:

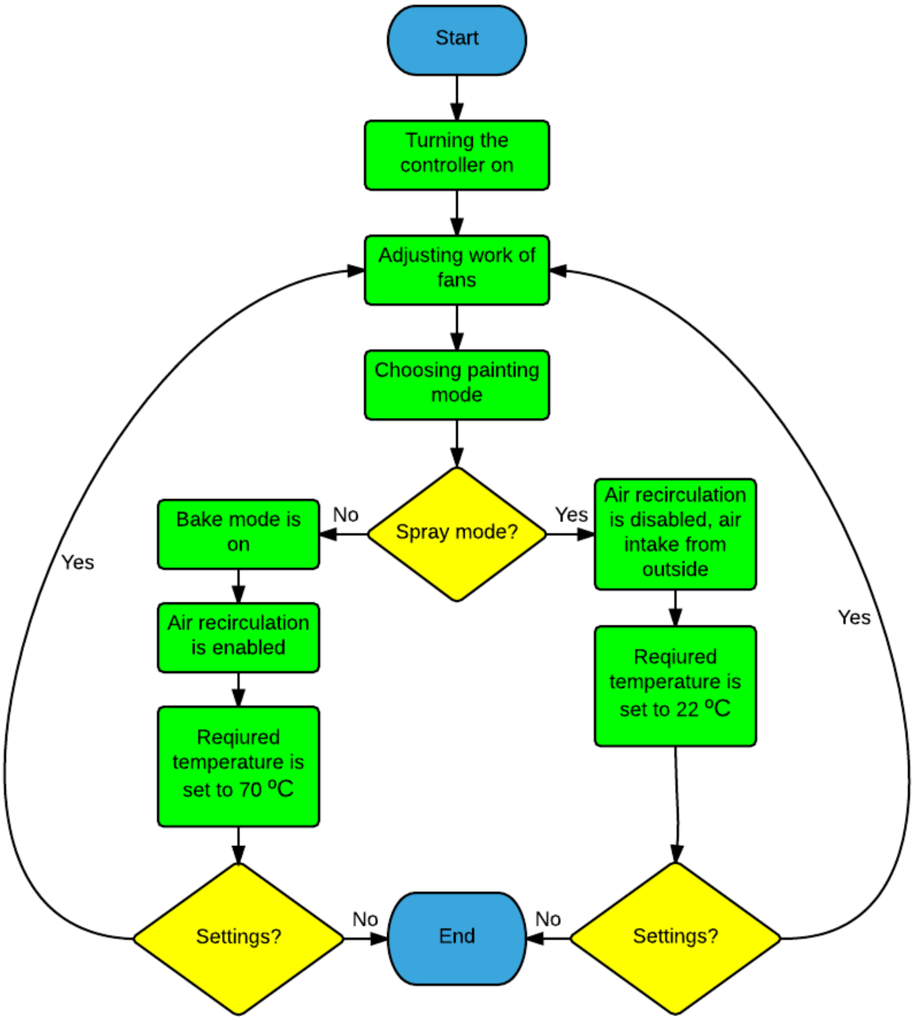


Fig.46. Block scheme of the ventilation process during painting

Program, meeting all the requirements is shown below:

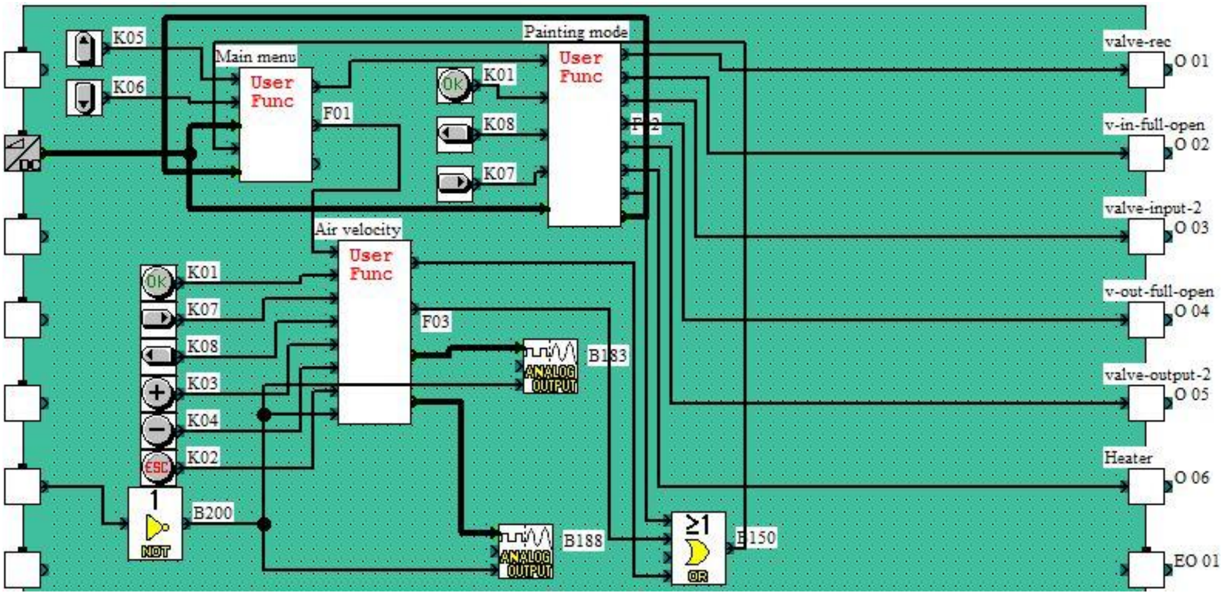


Fig.47. Control program for the controller

The program is divided on 3 blocks:

1) Main menu – responsible for working of the controller menu

2) Painting mode – responsible for the working mode of the painting chamber

3) Air velocity – responsible for working of the fans

<u>3.9 Description of the program</u>

3.9.1 Main menu

Menu is necessary for information view and possibility to reach settings. It should be informative and easy to use. Menu consists of 3 windows (Fig.48):

a) Information window – shows current temperature and painting mode

b) Painting mode option

c) Air velocity option

Switching between windows is possible using „UP“ and „DOWN“ arrows on the controller.

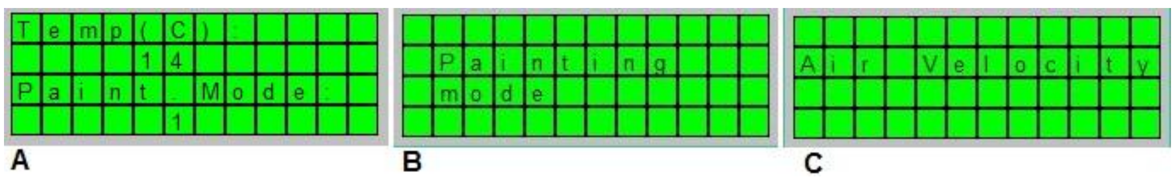


Fig.48. Main menu

3.9.2 Painting mode

„Painting mode“ menu allows to choose spray mode or bake mode. Each mode affect on heater working and position of valves. In spray mode, recirculation valve is closed, „IN“ valve and „OUT“ valve are opened and temperature range in painting chamber is 20-24 ºC. On the information window, spray mode is shown as „1“ and it is set as a default mode (spray mode is on with switching on of the controller). In bake mode, recirculation valve is opened, „IN“ valve and „OUT“ valves are fully closed until the air in painting chamber reaches required temperature. Then, „IN“ and „OUT“ valves open at 20% to fill circulated air with fresh air and eliminate moisture and paint vapors. This is an effective way to quickly reach required temperature and consume less fuel. On the information window, bake mode is shown as „2“. To choose required mode, find „Painting mode“ window in main menu and press „OK“ button. Then, in appeared window, choose required mode: spray mode –„LEFT“ arrow and bake mode – „RIGHT“ arrow (Fig.49).

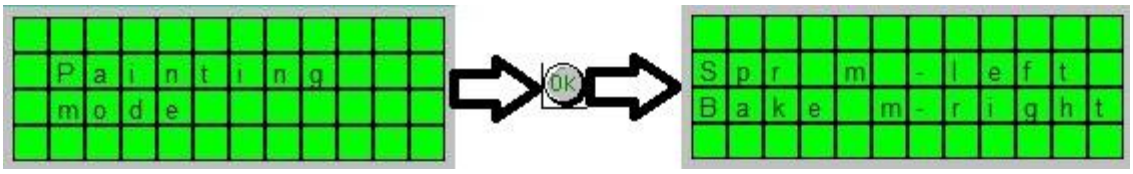


Fig.49. Settings of the painting mode

„Painting mode“ block itself is shown below:

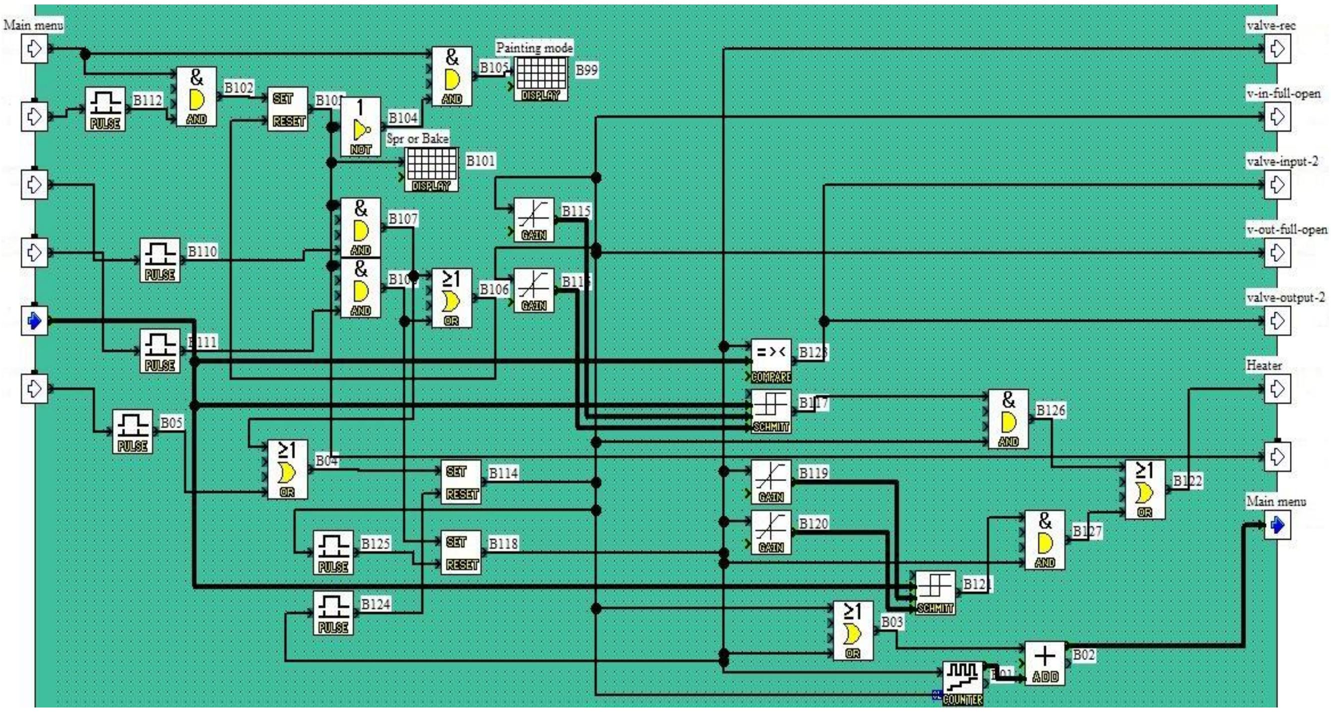


Fig.50. „Painting mode“ block

3.9.3 Air velocity

„Air velocity“ menu allows to regulate rotation speed of the fans. It is necessary to regulate the pressure in the painting chamber or to establish required painting conditions. This function is realised using analog output signal (0-10) V, where 0V – 0 $\frac{1}{\min}$ and 10 V – maximum rotation speed. This is possible using expansion module „AL2-2DA“. To regulate rotation speed, find „Air velocity“ window in main menu and press „OK“ button. Appeared window allows to choose fan, which rotation speed needs to be changed: „LEFT“ arrow – exhaust fan, „RIGHT“ arrow – supply fan. After choosing of the fan, it is possible to increase rotation speed („+“ button) or decrease rotation speed („-“ button) (Fig.51). Return to main menu using „ESC“ button.

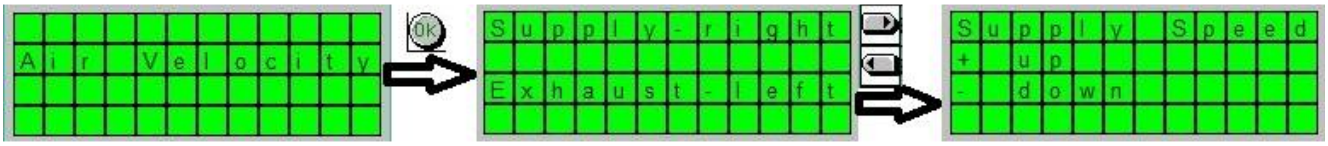


Fig.51. Settings of the air velocity

Step of the regulation is 1 V, so in all, there is 10 steps of the rotation speed. Calculated parameters of the fans are achieved on 9V – 2900 $\frac{1}{\min}$ on the supply fan and 3200 $\frac{1}{\min}$ on the exhaust fan. This step of the rotation speed is set as a default (9 V is set with switching on of the controller). „Air velocity“ block itself is shown below:

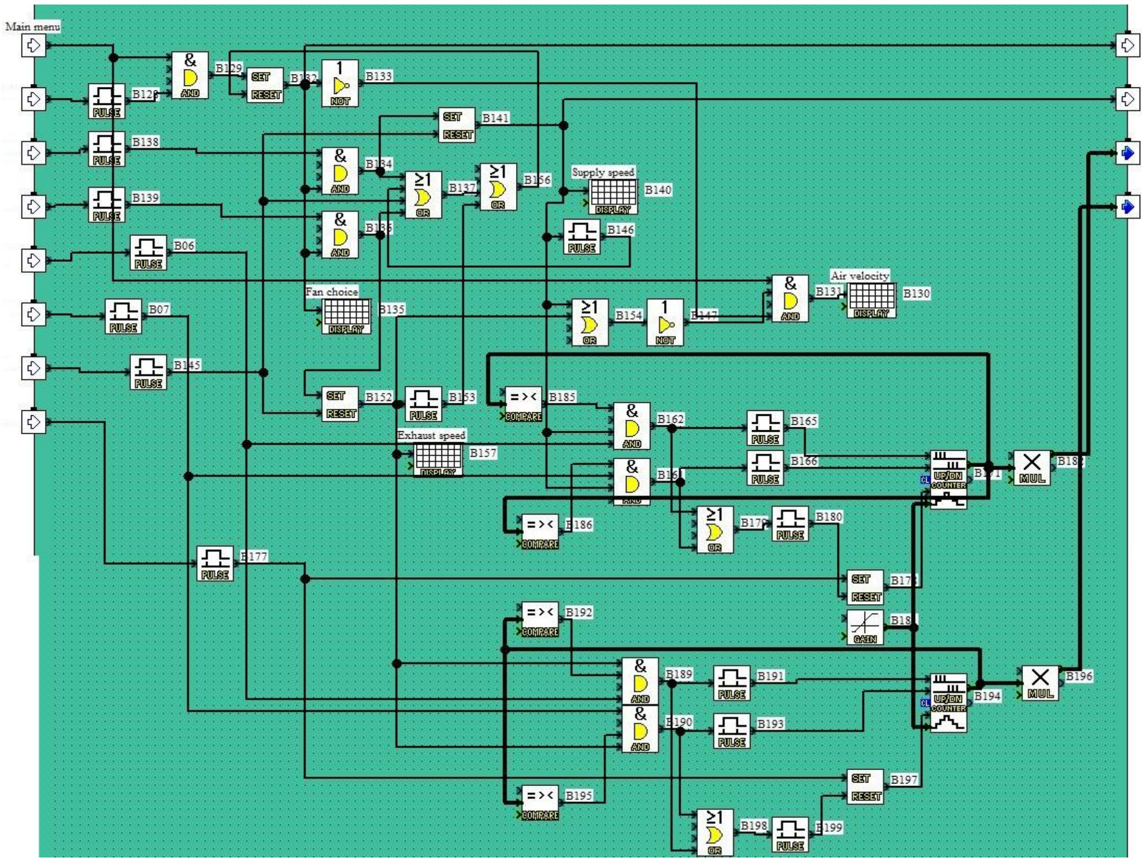


Fig.52. „Air velocity“ block

3.10 Security

3.10.1 Fuses

Electrical equipment needs to be protected from overload, overheating or short circuits. For that purpose, fuses, shown as F on electrical scheme (Fig.31), have to be installed. Its working principle is based on current value: if it exceeds specified value of the fuse, it burns down. In datasheet for frequency converters, manufacturer provides necessary information about protection of the devices:

Tab.9. Parameters of the fuses [38]

Type	Fuses		Size of copper conductor in cablings					
ACS310-	gG	UL Class T (600 V)	Supply (U1, V1, W1)		Motor (U2, V2, W2)		PE	
x = E/U	A	A	mm^2	AWG	mm^2	AWG	mm^2	AWG
03x-13A8-4	25	30	6.0	10	6	10	6.0	10
03x-17A2-4	35	35	6.0	8	6	8	6.0	8
03x-25A4-4	50	50	10.0	8	10	8	10.0	8
03x-34A1-4	80	80	16.0	6	16	6	16.0	6
03x-41A8-4	100	100	25.0	4	16	4	16.0	4
03x-48A4-4	100	100	25.0	4	25	4	16.0	4

Required current value of the fuse for frequency converter of the exhaust fan is marked in red field and for frequency converter of the supply fan it is marked in blue field. Abbreviation „gG" is related to European Standard „IEC 60269"[39] and „UL"[40] is the American Standard. Fuses with required parameters are widespread on Estonian market and manufacturer „ABB" is also offers its fuses corresponding to „gG" safety class:

Fig.53. „ABB" fuses with „gG" safety class [41]

3.10.2 Stop switch

For contingency events dangerous for health or unsafe for equipment, emergency button, shown as SB on electrical scheme (Fig.31), have to be installed. The aim of the button is to break electrical circuit of all ventilation system. That is why, the button should have locking mechanism and disable all three phases at once.

Fig.54. Stop switch [42]

4. Exploitation and price analysis

4.1 Operation manual and accident prevention

To start ventilation system working, it is only required to turn the controller on, in case that stop switch comletes the circuit. The controller sends control signals to frequency converters and opens necessary valves. It starts working on default settings (spray mode is on and both fans on its nominal load). After the ventilation system is on, it is possible to adjust settings as described in topic 3.9.

Car painting is an area, where work mostly related with poisonous chemicals. That is why personal protective equipment (PPE), such as glasses, gloves, respirators, protective clothing, is necessary.

4.1.1 Respirators

To prevent inhalation of the chemical vapors and dust, a mask, called respirator is used. In painting industry two types of respirators are mainly used: dust respirators and gas respirators. Dust respirators are required during preparation works: grinding, polish. According to european standard EN149, dust respirators are divided on three protection classes: P1, P2, P3.

Tab.10. EN149 protection classes [5]

Protection class	Efficiency (%)	Occupational Exposure Limit
P1	78	4x
P2	92	12x
P3	98	50x

Occupational Exposure Limit – maximum allowed concentration of contaminants in the air during 8-hour work day. In preparation works, it is recommended to use at least P2 protection class respirator.

Gas respirator protects from dust and from vapors. It consists of prefilter – protects from dust and main filter – contains active components to neutralize harmful substances. Gas respirators are used during painting. According to european standard EN141, gas and vapour filters are divided on area of use and each type has its own colour. Car painting requires A type gas respirators.

For use against	Filter Type	Colour Code	Main Applications
Gas and vapour EN 141	A	Brown	Organic vapours with boiling point greater than 65°C and good warning properties
	B	Grey	Inorganic gases and vapours e.g. chlorine
	E	Yellow	Acid gases and vapours e.g. sulphur dioxide, hydrogen chloride
	K	Green	Ammonia and organic ammonia derivatives

Fig.55. EN141 – gas and vapour filtration [43]

4.1.2 Protective clothing

As respirators, protective clothing is also different for preparation work and for painting work. Clothing for preparation works should protect from dust and have breathability. In addition, items, such as zip closure or buttons, should be hidden to prevent accidentally surface damage. Clothing for painting works is only used during painting. It should prevent paint hitting on the skin and hair. Painting suit is usually made of paint repulsive materials (nylon).

Fig.56. Protective clothing [5]

4.2 Filtration

Using of chemicals requires not only specific PPE, but also an effective filtration responded to European Standards. It is necessary not only for protection of the environment, but also for qualitative painting. In modern painting chambers, three filtration steps are applid. The first filtration step is set before supply fan (Fig. 57). It is the coarse panel filter and its aim is to clean incoming air from big polluting particles, which can damage fan peels. Filter clean class have to correspond to class G2-G4 (Tab.7). The distance between the fan and the duct is 530 mm. It means that filter length cannot exceed 500 mm and overall dimensions are (500x400x800) mm (LxHxW). On estonian market, a wide variety of filters corresponding to EN779 are offered by „Balti-Filtrid“ company. Required dimensions of the filter are not among standard dimensions, but it is possible to order specific dimensions.

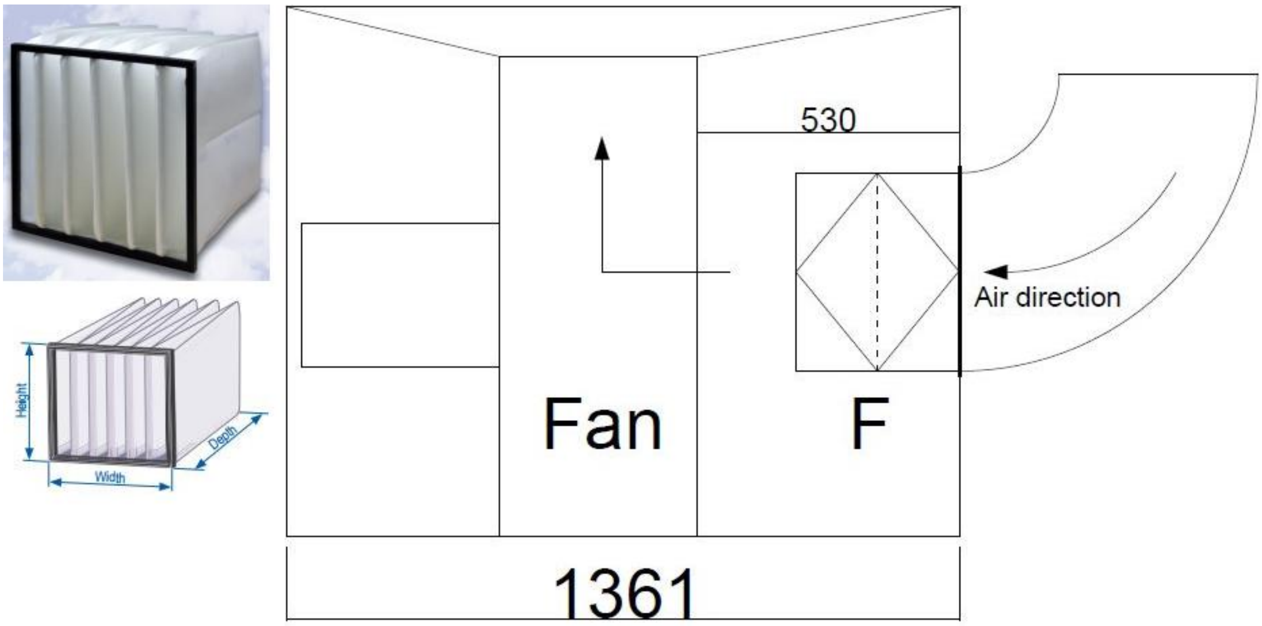


Fig.57. 1st filtration step [44]

The second filtration step is set on the ceiling. It is special filtration material, its aim is to clean incoming air from dust and synthetic particles to keep painting surface clean. Cleaning class of the ceiling filter have to correspond to M5-M6 (Tab.7). This filtration material is available in rolls. For installation, it is cut on required pieces and is set in prepared cells on ceiling (Fig.58). Requirement material, meeting all the requirements is available in „Balti-Filtrid“ with standard roll dimension (2x20)m. Dimensions of the ceiling in painting chamber is (5940x3050) mm. It means, that it is enough of one roll to install filtration material on ceiling two times.

Fig.58. 2nd filtration step [45]

The third filtration step is set under the floor. It is special filtration material, its aim is to clean air from chemical vapors (paint, varnish). It is necessary for environmental preservation and to eliminate a threat for health. Cleaning class of the floor filter have to correspond to G2-G4 (Tab.7) with paint absorbing properties. For installation, it is cut on required pieces and is set in floor grate (Fig.59). As the ceiling filter, it is available in rolls. Requirement material, meeting all the requirements is available in „Balti-Filtrid“, filter is called „Paint stop“ and is coloured with green. Standard roll dimension (2x20) m. It means, that it is enough of one roll to install filtration material in floor two times.

Fig.59. 3rd filtration step [46]

4.3 Painting chamber price analysis

The aim of the price analysis is to compare cost of a new assembled painting chamber with cost of ventilation system installation in already existed workroom. Now, when information about all necessary components is gathered, it is possible to calculate cost of installation.

Product	Q-ty	Price (€)	Description	Information link
heat exchange module "MT 8 2017.2.2 "	1	1 887,91	heat exchanger	http://modern-tech.ru/price.html
burner "LBG EM 35-E"	1	2 392,63	heating source	http://modern-tech.ru/price.html
supply fan "CFL 450"	1	1225,69	fan for air intake	http://www.dometrics.com/catalog/
exhaust fan "CFL 400"	1	1039,59	fan for air outtake	http://www.dometrics.com/catalog/
frequency converter "ACS310-03E-17A2-4"	1	415,501	frequency converter to control supply fan	http://www.elektroskandia.ee/hinnakiri
frequency converter "ACS310-03E-13A8-4"	1	338,463	frequency converter to control exhaust fan	http://www.elektroskandia.ee/hinnakiri
controller "Mitsubishi Aplha 2"	1	141,4	Control unit for ventilation	http://www.elfadistrelec.ee/
expansion module „AL2-2DA“	1	79,4	Necessary for having analog outputs	http://www.elfadistrelec.ee/
Regulation valves „JSMMU“	3	422,64	Air circulation control	http://www.lindab.com/uk/
90º ventilation knee (400x800)	1	58,75	floor - exhaust fan connection	http://www.etsnord.com/hinnakiri
90º ventilation knee (800x400)	1	58,75	ventilation tee - supply fan connection	http://www.etsnord.com/hinnakiri
Ventilation tee (400x800)	2	150,08	Ventilation system elements	http://www.etsnord.com/hinnakiri
Duct (400x800) L: 2384mm	2	174,83	Ventilation system elements	http://www.etsnord.com/hinnakiri
tip (400x800) with net	2	173,82	Ventilation system elements	http://www.etsnord.com/hinnakiri
90º ventilation knee (1095x1361)->(400x1361)	1	269,41	Non standard element	http://www.etsnord.com/hinnakiri

Coarse filter - G3 (800x400)	1	42,24	Filter installed before supply filter to clean incoming air	http://www.filtrimeister.ee
Ceiling filter - 1 roll (2x20) m	1	78	Medium filter on the ceiling	http://baltifiltrid.ee/filterkangad/
"Paint stop" filter – 1 roll (2x20) m	1	59	Floor filter with paint resistant properties	http://baltifiltrid.ee
Power supply „Mean Well DR-45-24“	1	21,5	Power supply for controller and temperature sensor	http://www.elfadistrelec.ee/
Temperature sensor "ATM2-U"	1	62,65	Sensor for measuring temperature in painting chamber	http://www.elfadistrelec.ee/
Another electrical equipment		300	Wires, relays, DIN rail, mounting	http://www.elfadistrelec.ee/
	TOTAL:	9 392,25 €		

Calculated total price does not contain expenses on shipping, mounting and design. Price on shipping can be obtained only after an equipment is ordered. Mounting price may widely vary depending on the contractor. However, missing prices will not significantly affect on economical analysis, since same costs have to be spent on a new assembled painting chamber. The analysis shows, that construction of the ventilation system in existing workroom is about 2 times cheaper than buying a new painting chamber. It is even cheaper, than a chinese painting chambers, so the conclusion is clear – it is totally worth to construct ventilation system in existing workroom.

Conclusion

To design ventilation system for workroom, a big research work is done. Technical material, such as painting theory, working principle of painting chamber, is studied. As a result, modern and efficient painting chamber, corresponded to all required European Standards, is created. However, there is still options, that could make designed painting chamber better, such as automatic regulation of pressure or installation of recuperation system. In the course of doing work, i have faced with specific industrial equipment, such as fans and heaters, ventilation features and its calculations. In addition, it was necessary to unite all the processes in one system and automate it. So, in all, this work positively affected on my knowledges in ventilation and i have obtained priceless experience in area, i was not familiar with before. To conclude, it is important to say, that it is made a serious work on exploring of ventilation and car painting. The aim of the work is completed and results exceed expectations.

Summary

The aim of the thesis is to create ventilation system for workroom. Ventilation have to be energy efficient, highly automated and correspond to European Standards. To achieve high efficiency, ventilation has two fans: supply fan and exhaust fan. It allows to obtain high air flow rate and regulate pressure in painting chamber. Also, heat exchange unit is built in. It is required to heat incoming air to required temperature. As a fuel, gas is used, as the cheapest fuel available on market. To decrease fuel consumption and prolong exploitation time of heater, recirculation system of the air is built in. It allows to heat air to high temperatures by recirculating it through the heater. To regulate all the processes, automation of the ventilation is required. As the solution, PLC controller is used. It allows to regulate the work of supply fan and exhaust fan by changing rotation speed. Also, it is possible to choose painting mode: spray or bake mode. To implement automation, electrical equipment, such as frequency converters, temperature sensors and relays, is used. To avoid hitting of the polluting particles on painting surface and to prevent environmental pollution, it is important to have a good filtration of air. Designed ventilation has three filtration steps: coarse filtration, fine filtration and paint filtration. Coarse filtration prevents incoming air from big polluting particles, such as sand, leaves. Fine filtration prevents incoming air from small polluting particles, such as dust. Paint filtration cleans outcoming air from paint and varnish.

To design ventilation system, a variety of software is used: „AutoCad“ – to design a layout of workroom and electrical scheme, „Solid Edge“ – to create a 3D model of ventilation system, „AL-PCS/WIN-E“ – to create a program for PLC controller, „Microsoft Exel“ – formation of tables, „Microsoft Word“ – formation of thesis. In addition

Kokkuvõte

Töö eesmärk on luua ventilatsioonisüsteem töökoja jaoks. Ventilatsioon peab olema energiliselt efektiivne, kõrgelt automatiseeritud ja vastama Euroopa Standardite nõuetele. Kõrge kasuteguri saavutamiseks, ventilatsioonis on kasutatud kaks ventilaatorit: sissepuhe ventilaator ja väljatõmme ventilaator. See võimaldab saada kõrge õhuvoolu hulka ja reguleerida rõhku värvimiskambris. Lisaks, soojusvaheti on sisse ehitatud. Seda on vaja sisseliikuva õhu soojendamiseks kindla temperatuurini. Kütuseks, on kasutatud maagaasi, kuna see on odavaim kütus turul. Kütusekulu alandamiseks ja ekspluatatsiooni aja pikendamiseks, ventilatsioonis on kasutatud õhu retsirkuleerimissüsteem. See võimaldab soojendada õhku kõrge temperatuurini retsirkuleerides seda soojusvaheti läbi. Protsesside reguleerimiseks, on vaja ventilatsiooni automatiseerida, selleks on kasutatud PLC kontrollerit. See võimaldab reguleerida sissepuhe ja väljatõmme ventilaatorite kiirust ja valida värvimiskambri tööviisi: värvimisviis või kuivatusviis. Automatiseerimise rakendamiseks, on kasutatud sellisi elektrilisi seadmeid, nagu sagedusmuundurid, temperatuuriandurid ja releed. Selleks, et vältida saasteainete sattumist värvimispinnale ja keskkonna saastamist, on oluline paigaldada õhu filtreerimissüsteemi. Projekteeritud ventilatsioon omab kolm filtreerimissammu: jäme filtreerimine, peen filtreerimine ja värvi filtreerimine. Jäme filtreerimine puhastab sisseliikuva õhku suurtest saaste osadest, nagu liiv. Peen filtreerimine puhastab sisseliikuva õhku väiksete saaste osadest, nagu tolm. Värvi filtreerimine puhastab väljaliikuva õhku lakist ja värvist.

Värvimiskambri projekteerimiseks, on kasutatud järgmine tarkvara: „AutoCad“ - töökoja asetuse koostamiseks ja elektriskeemi projekteerimiseks, „Solid Edge“ – ventilatsiooni 3d mudeli moduleerimiseks, „AL-PCS/WIN-E“ – programmi koostamine PLC kontrolleri jaoks, „Microsoft Exel“ – tabelite moodustamiseks, „Microsoft Word“ – lõputöö koostamiseks.

References

[1] - http://energy.gov/energysaver/whole-house-ventilation **(11.01.2016)**

[2] - http://www.benefit.ee/public/Keretookoja_seadmed/Blowtherm/BLOWTHERM_Industrial_Spraybooth_2016.pdf **(14.01.2016)**

[3] – http://www.wolf-geisenfeld.de/en/surface-engineering/products/spray-dry-booths/spray-booths/taifuno-vision-car-and-van-spray-booth **(18.01.2016)**

[4] - https://www.easycalculation.com/unit-conversion/learn-cfm-calculation.php **(20.01.2016)**

[5] - http://www.innove.ee/UserFiles/Kutseharidus/%C3%95ppe-%20ja%20juhendmaterjalid/Automaalri_6pik_ametikoolidele_veebi.pdf **(23.01.2016)**

[6] - http://www.terrauniversal.com/cleanrooms/iso-classification-cleanroom-standards.php **(23.01.2016)**

[7] - http://www.engineeringtoolbox.com/sizing-ducts-d_207.html **(27.01.2016)**

[8] - http://www.engineeringtoolbox.com/duct-velocity-d_928.html **(27.01.2016)**

[9] - http://www.engineeringtoolbox.com/circular-ducts-d_1009.html **(30.01.2016)**

[10] - http://www.engineeringtoolbox.com/rectangular-ducts-d_1010.html **(30.01.2016)**

[11] - https://www.evs.ee/tooted/evs-844-2016 **(02.02.2016)**

[12] - http://zao-tst.ru/raschet-podbor-kaloriferov.html **(04.02.2016)**

[13] - http://modern-tech.ru/catalog/teploobmennje_bloki_diztoplivogaz_elektroenergiya.html **(08.02.2016)**

[14] - http://www.heatco.com/HESelection **(08.02.2016)**

[15] - http://www.powrmatic.co.uk/products/oem/browse/view/product/hem-dh-heat-exchange-module/ **(08.02.2016)**

[16] - http://metdesign.ru/poleznaia_informatciia/proektirovanie_ventiliatcii **(13.02.2016)**

[17] - http://www.ventportal.com/node/1054 **(14.02.2016)**

[18] - http://www.vokesair.com/news/5-things-you-need-to-know-about-en-779-2012 **(15.02.2016)**

[19] - http://www.directindustry.com/prod/novovent/product-19905-393509.html **(25.02.2016)**

[20] - http://www.izoteh.si/db/izoteh/file/izoteh_blowers_and_fans.pdf **(02.03.2016)**

[21] - http://www.elektror.de/en/series/CFM **(05.03.2016)**

[22] - http://pokraskainfo.com/pokrasochnaya-kamera/osnovnye-ponyatiya.html **(08.03.2016)**

[23] - https://www.systemair.com/ee/Eesti/Tooted/ventilaatorid-ja-lisatarvikud/lisatarvikud-ventilatsioonile/ventilatsiooniluugid/srk/SRK-80-50-KL-3-Jalusispjll/ **(12.03.2016)**

[24] - http://www.lindab.com/global/pro/products/pages/jsmm-jsmmu.aspx **(15.03.2016)**

[25] - http://www.abb.com/product/seitp322/f4ae6316e4c42b9244257b64003ea81d.aspx?tabKey=2&gid=ABB3AUA0000039634&cid=9AAC158912 **(17.03.2016)**

[26] - http://www.abb.com/product/seitp322/f4ae6316e4c42b9244257b64003ea81d.aspx?tabKey=2&gid=ABB3AUA0000039633 **(17.03.2016)**

[27] - http://www.elit.ee/docs/Automation/Schneider/ATV312HU75N4.pdf **(19.03.2016)**

[28] - http://www.elit.ee/docs/Automation/Schneider/ATV312HU55N4.pdf **(19.03.2016)**

[29] - http://www.belimo.com/pdf/f/LM230A-F_1_0_fr.pdf **(23.03.2016)**

[30] - http://www.farnell.com/datasheets/1717884.pdf **(24.03.2016)**

[31] - http://www.loxone.com/tl_files/loxone/downloads/datasheets/EN-UK/200003-outside-temperature-sensor.pdf **(26.03.2016)**

[32] - https://www.elfadistrelec.ee/Web/Downloads/_m/ul/ALTM_mul.pdf?mime=application%2Fpdf **(28.03.2016)**

[33] - http://www.termoplus.ro/instalatii-termice-incalzire/arzatoare-cu-gaze/em-e/manuale/m.inst.cod970023702_em35-eem40-2-eem40-m-e.pdf **(30.03.2016)**

[34] - http://www.elfadistrelec.ee/Web/Downloads/he/et/DR45_eng_datasheet.pdf?mime=application%2Fpdf **(02.04.2016)**

[35] - https://en.wikipedia.org/wiki/Programmable_logic_controller **(08.04.2016)**

[36] - http://www.hf.dk/Files/Billeder/Kataloger/ALPHA%20catalog.pdf **(10.04.2016)**

[37] - http://www.mitsubishielectric.com/fa/products/cnt/sac/index.html **(15.04.2016)**

[38] - https://library.e.abb.com/public/3ba7efdcc6f946469739964395a14a20/EN_ACS310_SFUM_D_A4_Screen.pdf **(18.04.2016)**

[39] - https://webstore.iec.ch/preview/info_iec60269-1%7Bed4.0%7Den_d.pdf **(19.04.2016)**

[40] - http://ep-de.mersen.com/fileadmin/user_upload/_common_/Training_Modules/TM_106_Low_Voltage_American_Canadian_Fuses_UL248_CSA_EN.pdf **(21.04.2016)**

[41] - http://uk.rs-online.com/web/c/fuses-sockets-circuit-breakers/fuses/centred-tag-fuses/ **(21.04.2016)**

[42] - http://sg.rs-online.com/web/p/emergency-stop-push-buttons/2195813/ **(22.04.2016)**

[43] - http://www.bocsafetyproducts.co.uk/common/resources/v68938_boc_06.pdf **(24.04.2016)**

[44] - http://baltifiltrid.ee/wp-content/uploads/2015/04/tooteleht-kottfilter-G3-G4.pdf **(26.04.2016)**

[45] - http://www.pandaspraybooth.com/panda-900/ **(26.04.2016)**

[46] - http://www.msd-group.ru/pokrasochnoe-oborudovanie/dlya-avtomobilej/avtomobilnye-okrasochno-sushilnye-kamery.html **(26.04.2016)**