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Energy efficient Supermarket Refrigeration with Ejectors

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Master's Thesis
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MASTER THESIS

for

Student Raul Calvo Hoyas

Fall 2014

Energy efficient Supermarket Refrigeration with Ejectors

Energieffektive butikkjøleanlegg med ejektorer.

Background and objective

There is a large transition in supermarket refrigeration with a strong focus on Energy consumption. High efficient system configurations with R744 are introduced in various locations throughout Europe; however, further improvements are necessary and possible, for example with use of the ejector-based expansion work recovery systems.

In order to efficiently apply ejectors in refrigeration units, individual operation curves of each particular ejector geometry must be first determined, either experimentally or by use of advanced modelling techniques (CFD modelling). In practice, experimental tests at laboratory remain the most effective way of generating the ejector performance maps.

Therefore, the thesis will be focused on experimental determination of operational characteristics for various ejector geometries planned to be utilised in the expansion work recovery system for supermarket refrigeration units.

The following tasks are to be considered:

1. Literature review on R744 ejector technology
2. Analysis of operating conditions for R744 ejectors working in expansion work recovery systems
3. Preparation of an experiment plan leading to generation of a set of individual performance maps for the investigated ejector geometries
4. Practical training at the multi-ejector test facility
5. Plan and perform test
6. Data processing and analysis of results
7. Make a scientific paper of the main results of the master thesis
8. Make proposal for further work

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Spanish, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. The final report in Word and PDF format, scientific paper and all other material and documents should be given to the academic supervisor in digital format on a DVD/CD-rom or a memory stick at the time of submission in DAIM.

☒ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, August 25th 2014

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Preface

This master thesis has been submitted to the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU). This work has been carried out during the fall semester of 2014, and it is the culmination of my five years degree in industrial engineering in the Universidad Politecnica de Valencia (UPV).

This work has been perform with both experimental and theoretical character during all the semester. I have found my work very interesting due to the challenge of doing something new related to the refrigeration using natural refrigerants, and also for doing an investigation promoting the energy efficiency and the reduction of environmental damage.

Last, I would like to thank all people with who I have worked in these five years and specially with who I have worked this semester, my lab supervisor at SINTEF Krystof Banasiak and my master thesis supervisor at NTNU Trygve Magne Eikevik, because they have guided my master thesis during this semester.

Trondheim, December 18, 2014

Raúl Calvo Hoyas

Abstract

Nowadays, the use of R744 or carbon dioxide has been increased as a working fluid in many refrigerant systems. Nevertheless, one disadvantage for use this refrigerant is the thermodynamic losses produced in the refrigerant system when the fluid is throttled. These losses are increased if the refrigerant system is working in transcritical operation conditions. But, there is an option and it consists of using an ejector instead of the conventional expansion valve in order to reduce the energy losses and to increase the energy efficiency of the R744 refrigerant system. Thus, the R744 ejector refrigeration system is converted into a real possibility comparing to the conventional refrigeration system and it provides a significant reduction of the environmental contamination.

This work has been performed with the purpose to increase the knowledge about how the ejector refrigeration system works at different operation conditions by means of an experimental analysis. Also, the test facility used in this experimental analysis is a two phase ejector refrigeration system with R744 as a working fluid. The experimental results obtained show that the ejector works more efficiently using a pressure lift between 4 and 9 bar and with a entrainment ratio from 0.10 to 0.48, approximately. Furthermore, the ejector efficiency achieves the higher values working with the pressure ratio between 1.1 to 1.35, and the highest efficiency is found at the pressure ratio of 1.275, approximately. Besides, it is demonstrated that working at high inlet temperatures the ejector efficiency is better than working at low temperatures. This is due to the fact that more energy is saved by the ejector working at high temperatures because the expansion work is bigger than using the ejector at low temperatures. Therefore, it is shown that the ejector performs more efficiently in warm climates than running the ejector in cold climates.

List of Figures

List of Graphics

List of Tables

List of Symbols and Abbreviations

Abbreviations

CFC	Chlorofluorocarbon
COP	Coefficient of Performance
CFD	Computational Fluid Dynamics
HCFC	Hydro Chlorofluorocarbons
R744	Refrigerant denomination for carbon dioxide
DIFF	Ejector diffusor outlet
MAX REC	Maximum recovery work
Ej	Ejector
Ej in	Ejector inlet
Ej out	Ejector outlet
MO	Ejector motive nozzle
SN	Ejector suction nozzle
GC	Discharge
REC	Recovered
ID	Identification
3D	three dimensions
2D	two dimensions

Symbols

η	Ejector efficiency
ε_n	Relative increase of entropy rate
ρ	Density
Π	Pressure ratio
Ω	Mass entrainment ratio
$\dot{W}$	Work rate
Δ	Lift
P	Pressure
S	Specific entropy
$\dot{S}$	Entropy rate
h	Specific enthalpy
T	Temperature
$\dot{m}$	Mass flow rate
kg	Kilogram
ºC	Celsius degree
mm	millimeter

Contents

1. Introduction

There are a lot of options which are able to lessen the effects of the Global warming. However, the energy efficiency is one of the most important solution in order to reduce the Global warming at the present. The effects of this problem have been increased much more in last years, so the World is more aware of this problem these days. Increasing energy efficiency we could decrease the cost of the energy development, we would be more energy efficient and less political controversial for a sustainable energetic future. Also, saving energy we can reduce emissions and costs in the infrastructure. Therefore, there are many reasons that make the efficiency the most important climate issue to reduce Global warming currently, even though, the improvement of energy efficient is higher for cold climate zones because of it is related to the higher heat recovery during the heat season.

Because of this, one of the energy targets of the European Union climate is the improvement of 20% in the European energy efficiency for 2020. In the last years, the European Commission has emphasized the importance to make the European economy less energy consumer and more environment-friendly. So, changing to a less carbon consumption at the future, the European Union could be using around 30% less energy in 2050 than in 2005(Roadmap2050, 2011). Therefore, it should be paid attention in optimization of heating and refrigeration in order to reduce the world energy consumption. Nowadays, the energy efficiency of supermarkets operations has gain more attention due to the escalating cost of the energy in the last years.

Hence, this makes the supermarket efficiency more important to increase the energy efficiency for all countries. In fact, the 50% of the total energy consumption by a supermarket is due to the refrigeration systems(Ducoulombier, Teyssedou et al. 2006). So, the improvement of refrigeration systems would be a better way to save energy and to decrease the Global warming. There are a lot of possibilities to upgrade the performance of refrigeration systems, such as: diminishing the quantity of refrigerant, decreasing the leakages of refrigerant, the use of natural refrigerants, the heat recovery of wasted energy, optimal control of refrigeration system, energy efficient design, etc.

Furthermore, supermarkets have an important role in the HCFC's regulation due to the necessity of keep a reasonable low concentration of green-house effect gases in the atmosphere. It is because of the fact that they leak up to 250 kg per year of the CFC's used as a refrigerant and are considered as major energy consuming indirectly contributing to CO_2 emissions in the commercial buildings area(Ducoulombier, Teyssedou et al. 2006).

Nowadays, the most part of the European refrigeration systems are using HFC-404A as working fluid. So, the average annual leakage rates in Europe are about 20% of the total fluid charge. Besides of that, the main refrigerant used in the world at the present is the HFC-22 and the HFC-404A is just about the 30%(Hafner, Försterling et al. 2014). Refrigerant systems applying natural refrigerants are not too common because of the necessity of technology development. However, the natural refrigerants have a large potential with respect to energy efficiency, cost efficiency and heat recovery. For example, the R-744 or carbon dioxide is the only refrigerant which has been developed and it is working in more than 2000 European supermarkets and the most part of these supermarkets are located in the Northern European countries.(Hafner, Försterling et al. 2014)

One of the drawbacks using R-744 as working fluid in refrigeration systems is related to the thermodynamic process of throttling the refrigerant because the thermodynamic losses connected to this are very substantial, specially when the system is working in transcritical mode. One option to take advantage of this situation is to expand the refrigerant through an ejector instead of use the conventional throttling valve. The ejector can contribute to improve the efficiency and the coefficient of performance (COP) of the cycle using the work that would have been dissipated by the throttling valve. However, if this option could be a good commercial alternative, the ejector refrigeration system should operate very steady at different operating conditions. In order to implement the ejector refrigeration system as a commercial system is necessary to know how the ejector operates at different set points.

Therefore, with the objective of increasing the use of natural working fluid such as R744, SINTEF Energy Research is working together with Danfoss, an important company in refrigeration technology, on a project working with ejector refrigeration systems. The main purpose of this project is the determination of the ejector capacity and the individual ejector performance at different operating conditions.

2. Ejector refrigeration system

There are many processes where important amounts of heat energy released are rejected to the surroundings as wasted energy. One method to recover this wasted energy is the ejector.

Ejectors are devices that are used to recover the expansion work lost during the throttling process in the refrigeration cycle by expanding-compressing a fluid. The expansion process begins in the condenser and then the vapour is compressed from the evaporator.

Ejector refrigeration system provides a promising way to generate a cooling effect by using alternatives sources like solar radiation or geothermal energy, and harvesting waste heat as the driving energy as generation energy. It is a simple system with low initial and running cost with long lifetime. Also, it can be possible using natural refrigerant as working fluids like R744, ammonia or propane. However, the main disadvantages of the ejector refrigeration system are the cost of exergy destruction (J. Chen et.al., 2014) and the relatively low COP, even though the relative low COP makes this system a good option for commercial use due to the less necessity of refrigeration in comparison to the industry.

Ejector system is a novel method which is not so extended in the industrial application. But, there are many studies that confirm the high efficiency of the ejector used as refrigeration system in comparison to the conventional refrigeration cycle. Moreover, it is important to emphasize that the efficiency of this refrigeration system depends on principally the room temperature and the ejector geometry.

But this is not a new system really, because the first ejector cycle was the ejector recirculation cycle patented by Phillips in 1938, and some later studies about this cycle show an experimental COP improvement of 13% using CO_2 as working fluid(Minetto, Brignoli et al. 2014). The following picture shows one-phase ejector refrigeration system:

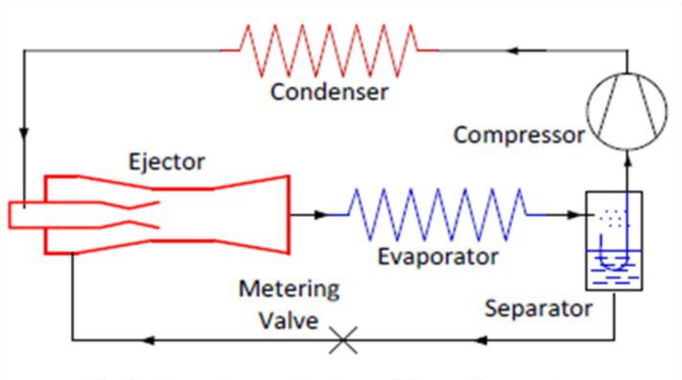


Fig.1: One-phase ejector refrigeration system
(N. Lawrence et.al., 2014)

Another system that could be used while maintaining the same technological base is the standard two-phase ejector cycle, in which the ejector is used to pump extra liquid through the evaporator. In this lay-out is used a separator by which it is possible to eliminate the liquid in the compressor and to recirculate the liquid into the ejector, as it can be seen in the figure 2.

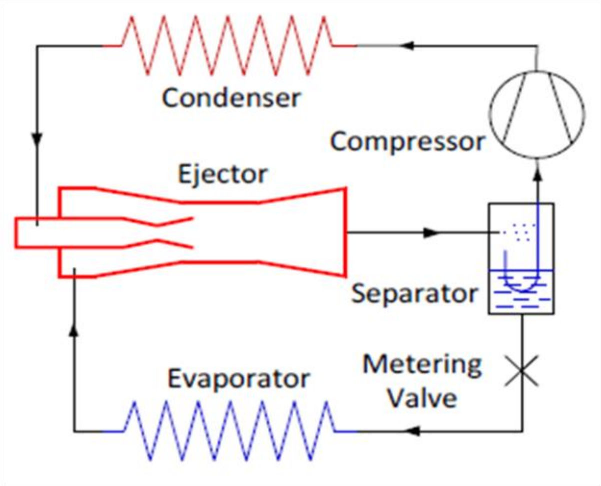


Fig.2: Two-phase ejector refrigeration system
(N. Lawrence et.al., 2014)

Much of recent work of this cycle has been focused on transcritical CO_2 systems due to the high throttling loss and the high potential improvement related with the throttling of transcritical CO_2 in the expansion valve cycle. Using this method, it is observed how COP and capacity improve by 8% in comparison to the conventional refrigeration system, and it could reach approximately to 18% the capacity of the cycle(Elbel and Hrnjak 2008).

Besides of this, there are two additional refrigeration cycles that incorporate two-phase ejectors with multiple evaporation temperatures, as it can see in the next picture. The first cycle was proposed by Oshitani in 2010, in which the two-phase flow discharged from the ejector is sent through an evaporator (high temperature), and then it is sent to the compressor. Also, the ejector pumps the flow into another evaporator (low temperature). The fluid leaving the condenser is split into two streams, the ejector motive stream and the ejector suction stream. The first stream enters the ejector motive nozzle and the suction stream is throttled, evaporated and then, it is sent to the ejector suction nozzle. The second option of refrigeration ejector cycle with two evaporation temperatures was proposed by Burk in 2006, and this way, the flow division is produced in the diffusor instead of in the condenser.(Lawrence and Elbel 2013)

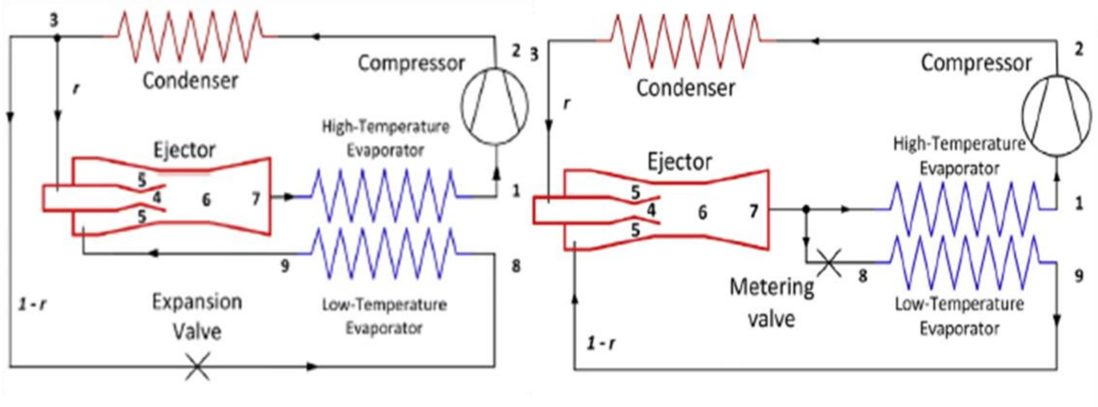


Fig.3: Oshitani & Burk ejector system
(N. Lawrence et.al., 2013)

The reason that there are different evaporation temperatures is due to the saturation temperature increase between the ejector suction and the diffuser produced by the pressure increase related with the ejector.

Multiple evaporation temperatures cycle can make heat transfer more effective in the evaporator than the single cycle whether the evaporators are being used to cool the same air stream because the temperature difference between the refrigerant and the air streams can be reduced working with multiple evaporator temperatures.(Lawrence and Elbel 2013)

Otherwise, one of the most important restriction is the effect of the condensing pressure in the refrigeration facilities. Ejection refrigeration system is not applicable when atmosphere is too high, so the condensation temperature for single stage ejector refrigeration system are between 30ºC to 40ºC (El-Dessouky, Ettouney et al. 2002). It could be possible the usage of two ejectors as it is showed in the next image. The first of them supplies low pressure fluid from evaporator, which leads to the production of evaporation capacity. The second ejector is applied to supply the stream from the first one, because of that the outlet pressure of the first ejector is reduced considerably ensuring a stable working of the ejector refrigeration system. Simultaneously, the extra power input might cause the COP drop depending on the generation, condensation and evaporation temperature.

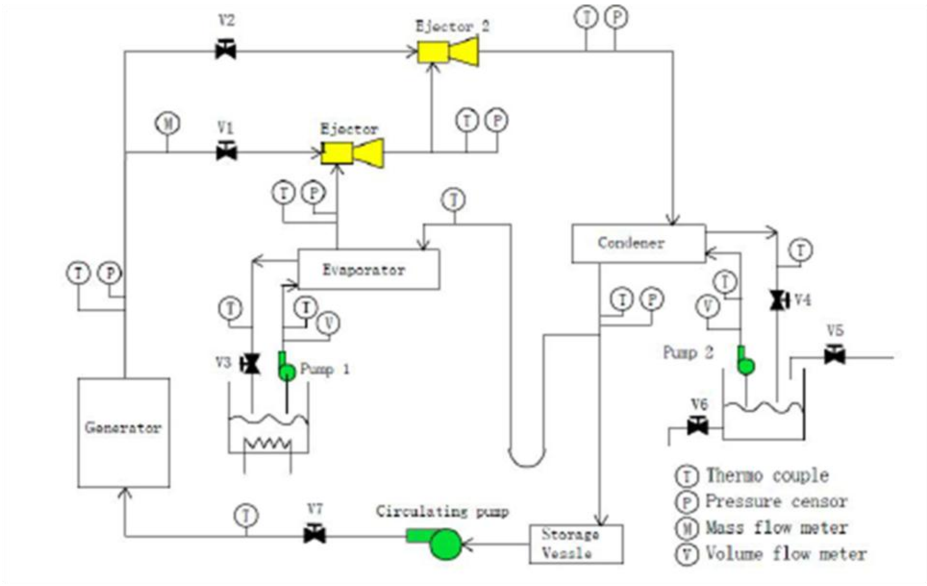


Fig. 4: Two-ejector refrigeration system
(Y. He et.al., 2014)

It is showed in a recent study that this system has important advantages under condensation temperature of 54 ºC, with generation temperature from 150 ºC to 130 ºC. However, if the condensation temperature is lower than 50 ºC, using single stage system is efficient enough (Y. He et.al., 2014). This lay-out expands the application range of ejection refrigeration systems.

Furthermore, the liquid-vapour separator can harm the overall performance of the system, due to the liquid that exits of the vapour outlet in the separator increases compressor work and decreases cooling capacity, both of which are an important contribution to COP decrease.

However, the separator allows saturated liquid to be fed into the evaporator producing several benefits in the refrigeration cycle performance, such as the absene of vapour in the flow that decreases the pressure drop through the evaporator. Besides of this, R744 has increased heat transfer coefficient at lower qualities and if a heat exchanger with headers is used, a very low quality fluid would be easier to distribute more uniformly (N. Lawrence et.al., 2014).

Therefore, as there are different types of ejectors systems, there are also different advantages and disadvantages depending on which the kind of ejector refrigeration cycle is used. In the particular case of the usage of ejector refrigeration system for supermarkets seems to be more convenient the systems with two evaporation temperatures due to the fact that in supermarkets are necessary cooling and freezing temperature.

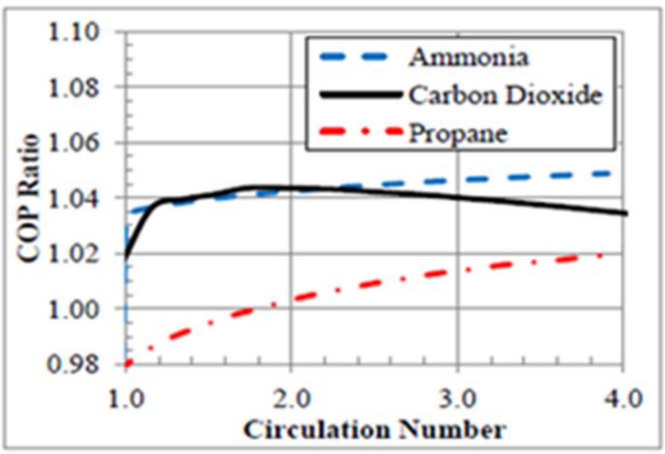
3. Use of R774 as working fluid in ejector refrigeration system

The average annual leakage rates of European supermarkets using HFC as working fluid are approximately 20% of the total refrigerant charge. The commercial refrigeration leakage rates are about 30%, being HCFC 22 the most common refrigerant currently used(Hafner, Försterling et al. 2014).

Therefore, it is important the improvement of the efficiency of this rates and the use of novel refrigerants such as natural refrigerants like propane, ammonia or carbon dioxide. In fact, relevant studies show important improvements in R744 system efficiency when heat recovery has been assumed in the process.

Moreover, there are several studies that show the use of ejector refrigeration system with R744 or carbon dioxide are a good option for being a work recovery device demonstrating to keep a substantial energy efficiency benefit currently. R744 ejectors might improve the system efficiency approximately by 15%, it depends on the room temperature of the heat rejection device of the refrigeration system(Hafner, Försterling et al. 2014). R744 ejectors are specifically available for heat recovery applications because of their operation mode close to the critical point. Due to this fact, trancritical R744 process are becoming the refrigeration system more selected for European supermarkets.

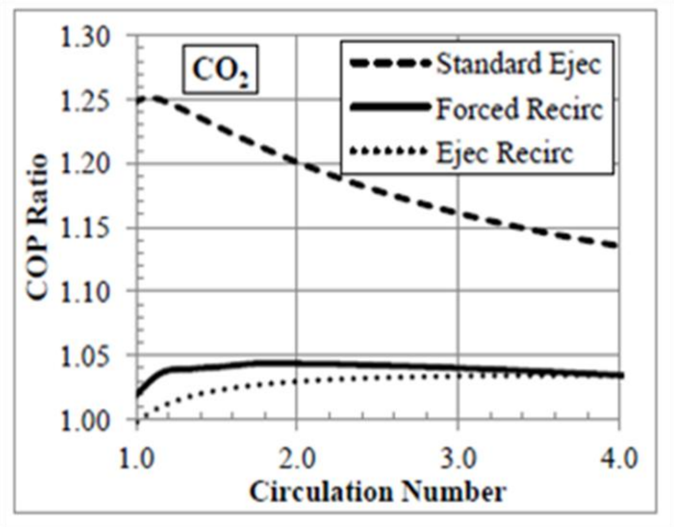
However, refrigerants mentioned above are not the only ones, there are also natural refrigerants, which are increasingly used in order to reduce the contamination and the green-house effect produced by CFCs. To know what type of refrigerant should be used is necessary to know how the system works and moreover, the characteristics of the cycle and the demand to supply. As it can see in the next graphic, each refrigerant works with different coefficient of performance according to the circulation number.



Graphic 1: Comparison of ejector performance between different natural refrigerants
(N. Lawrence et.al., 2014)

Therefore, several studies prove that R744 achieves its highest flow boiling heat transfer coefficient at very low quality due to its strong nucleate boiling compare to other refrigerants and if mass flux is increased, it does not improve the performance so much. Because of that, the COP of the R744 forced circulation cycle peaks at lower circulation number and then decreases due to increased pressure drop and pumping power at higher circulation numbers, as it can see in the graphic below.

Also, R744 provides the highest COP with the standard ejector cycle because of the fact that carbon dioxide gains benefit from recovering expansion work with the ejector than from the liquid recirculation, as it can see in the graphic below. As a result of this, it would be better if the power recovered by the ejector were used for pressure increase rather than to provide recirculation effect in the standard ejector cycle, then the COP could improve until 25% with a circulation number greater than unity (N.Lawrence et.al., 2014).



Graphic 2: R744 ejector performance working in different ways
(N. Lawrence et.al., 2014)

Thus, it is demonstrated that R744 should use the ejector to lift the compressor suction pressure instead of provide the recirculation effect. Whereas fluids like ammonia that can not recover as much power as carbon dioxide in the ejector, this type of refrigerant should be used to provide the liquid recirculation by the ejector system.

4. Multi-ejector refrigeration system

The most important objective of a supermarket refrigeration system is keep the thermal conditions inside the cooling cabinets and the building. So, it is necessary to emphasize that the ejector refrigeration system has to adapt according to the different loads and to outside temperatures. Thereupon, the COP's improvement of the ejector is nearly related to the control concept of the refrigeration system, and according to the climatic evolution of an specific area, it will be fundamental a distinctive control strategy in order to improve the efficiency of the cycle.

One possible option to improve the control of the different loads are the use of multi-ejector system. Using multi-ejector system instead of single ejector, the process can adapt better to the climatic changes or to the supermarket's demand variation. According to different investigations in the past, multi-ejector R744 systems increase by up to 20% at high room temperature or high return temperature from the heat recovery system(Hafner, Försterling et al. 2014). Recent and on-going studies show that this layout can increase the efficiency at low outside temperatures, which means that the multi-ejector could be the future refrigeration system in the Northern and Mediterranean Europe.

Nevertheless, the problem of using the carbon dioxide as working refrigerant fluid at high room temperature, like in Spain, is its high specific volume when it is working in the transcritical point and a direct consequence of this is the COP decrease. So, it is necessary to talk about possible ways to increase the COP either transcritical or subcritical process. There are several options to improve the COP of carbon dioxide systems working at high room temperatures as the implementation of an external subcooling unit based on conventional ejectors with a hydrocarbon as working fluid (J. Schönenberger et.al., 2014). Another possibility could be the utilization of parallel compression at high and low evaporation temperature facilities since 2010.

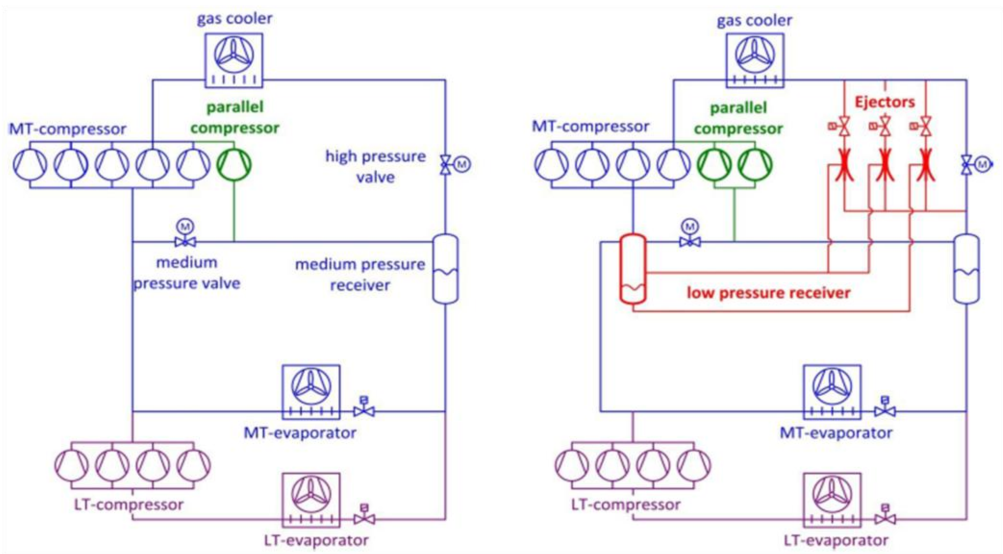


Fig. 5: Ejector system with parallel compression supplying high and low evaporation temperature (J. Schönenberger et.al., 2014)

As it can see in the previous graphic, there are three ejectors which recover the expansion work loss partly the expansion work lost in the basic cycle, and this work is used to recirculate liquid and vapour from the low pressure receiver of the medium temperature evaporators back to the medium pressure receiver. This efficiency improvement is owing to the evaporation temperature rise which produces a significant decrease of the frost formation in the facilities improving the system efficiency and the maintenance of the refrigeration installation.

Besides, the number of ejectors should be higher than three, to be able to achieve the high side pressure set points to many on/off switches of ejectors (Hafner, Försterling et al. 2014). In fact, if the number of the ejector in the facilities is highest, the efficiency of the system improves proportionally. This is due to the fact that the cycle is able to adapt better to a wide range of load requirements, because the different ejector geometries provide distinct operation points of each ejector.

Thus, it is demonstrated an increase of energy efficiency approximately by 14% using the ejector R744 systems compared to the basic system with parallel compression in Northern European climate and it would be by 20% in Southern European climate (J. Schönenberger et.al., 2014). This is because of the climatic conditions dependence and the use of the heat recovery in the process. Furthermore, it could increase the efficiency of the process if the low evaporation temperature were risen.

In conclusion, multi-ejector refrigeration system is able to perform in an ample range of climatic conditions and in different demands. The efficiency of this cycle depends on the discharge pressure and temperature, evaporation pressure and pressure lift, i.e., the operation conditions and the outside temperature.

5. Influence of ejector geometry on the ejector refrigeration system

As it has mentioned before, the ejector's efficiency and the COP's improvement depends on the ejector's geometry fundamentally. The operational mode of the ejector refrigeration system is related to the different lengths and angles of each part of the ejector.So, it is going to describe the relations of the performance parameters and the geometry of the ejector, even though, there are not so many studies explaining this relation.

As stated, the parts of the ejector more significant in the refrigeration system performance are essentially the motive nozzle, the mixing section and the diffuser.

Firstly, the motive nozzle of the ejector regulates the motive flow expansion and the flow rate. If the nozzle diameter is so small, the maximum motive flow rate would be under the necessary values of it, whereas if the nozzle diameter is so large, it reduces the flow admission as a result of an under-expansion of the motive flow. Also, it is necessary to find the right motive nozzle throat diameter for obtaining reasonable ejector cycle performance (Lee, Kim et al. 2011). Besides, it is found a relatively low percentage of the total irreversibility in the motive and suction nozzles, approximately it is less than 15 % in total for both nozzles (K.Banasiak et.al., 2014).

However, it is shown in several studies that the angle and length of the motive nozzle diverging section would not be expected to have very significant effects on the overall performance of R744 ejectors (N. Lawrenece et. al. , 2014).

Secondly, the ejector mixing section is where the suction flow is blended with the motive flow. Before of this, there is a converging section where is produced an acceleration of the suction flow before the mixture of both flows at the motive nozzle outlet. Whether the mixing section is too long, it could appear frictional losses in the process, on the other hand, if the mixing section is too short, there are not enough time to blend and to start to recover pressure. It is demonstrated that the mixing section length of 15 mm results in the best cycle performance and the highest ejector efficiency, it is approximately by 17%. Nevertheless, incorrect mixing length could reduce the COP by 10% (Nakagawa, Marasigan et al. 2011).

Otherwise, an important parameter is the ejector area ratio because it controls the quantity of suction flow, respect to any amount of motive flow, that can enter the ejector. If it is too small, it could occur that there is not enough area for both streams in the mixing section, so the amount of suction flow would have a maximum that can not exceed. But, if the ejector area ratio is too large, the suction stream could not mix with the motive stream. Then, it is important in order to choose the ejector area ratio takes into account the fluid that it is going to use, and in this case is R744 (N. Lawrence et.al. , 2014).

Finally, the ejector diffuser is where the pressure recovery of suction and motive flows is concluded. If the diffuser angle is too small, this results in an excessive pressure drop, whereas if it is too large, it could occur a stream separation and an efficiency leakage. It was observed a better performance in the ejector with a longer diffuser(Banasiak and Hafner 2011).

So, it is showed that the mixing section and the diffuser are responsible to the pressure recovery, then it is important a good diffuser design for a great performance ejector (Elbel 2011). Also, there are higher losses observed for mixing section and diffuser approximately by 49% and 63% respectively, of the total irreversibility (K. Banasiak et.al., 2014).

Nevertheless, another study shows that geometry changes in mixing area have more effect in the ejector performance than changes in the diffuser angle (Banasiak, Hafner et al. 2012). Therefore, it is more important the optimal design of the mixing section than the diffuser design to improve the COP and the efficiency of the system.

In conclusion, based on the limited studies that related the influence of the ejector geometry with the ejector refrigeration system performance, it could emphasize the importance of the ejector design depending on the density of the working fluid and the different temperatures of work. But, it would be necessary more specific studies about this relationship to improve the efficiency of the ejector refrigeration system.

6. Ejector theory

6.1. Ejector working principle

The ejector is a static device with a simple principle of working. Nevertheless, there are various concepts related with the ejector flow that makes a hard task to control and analyse the ejector performance.

The ejector working principles are based on the Venturi effect, that occurs in the motive nozzle, and the momentum conservation in the mixing chamber between the motive and the suction flows. As it can see in the next figure, the main flow is accelerated through a converging-diverging nozzle in the zone 1, converting a big amount of energy in the motive flow into kinetic energy.

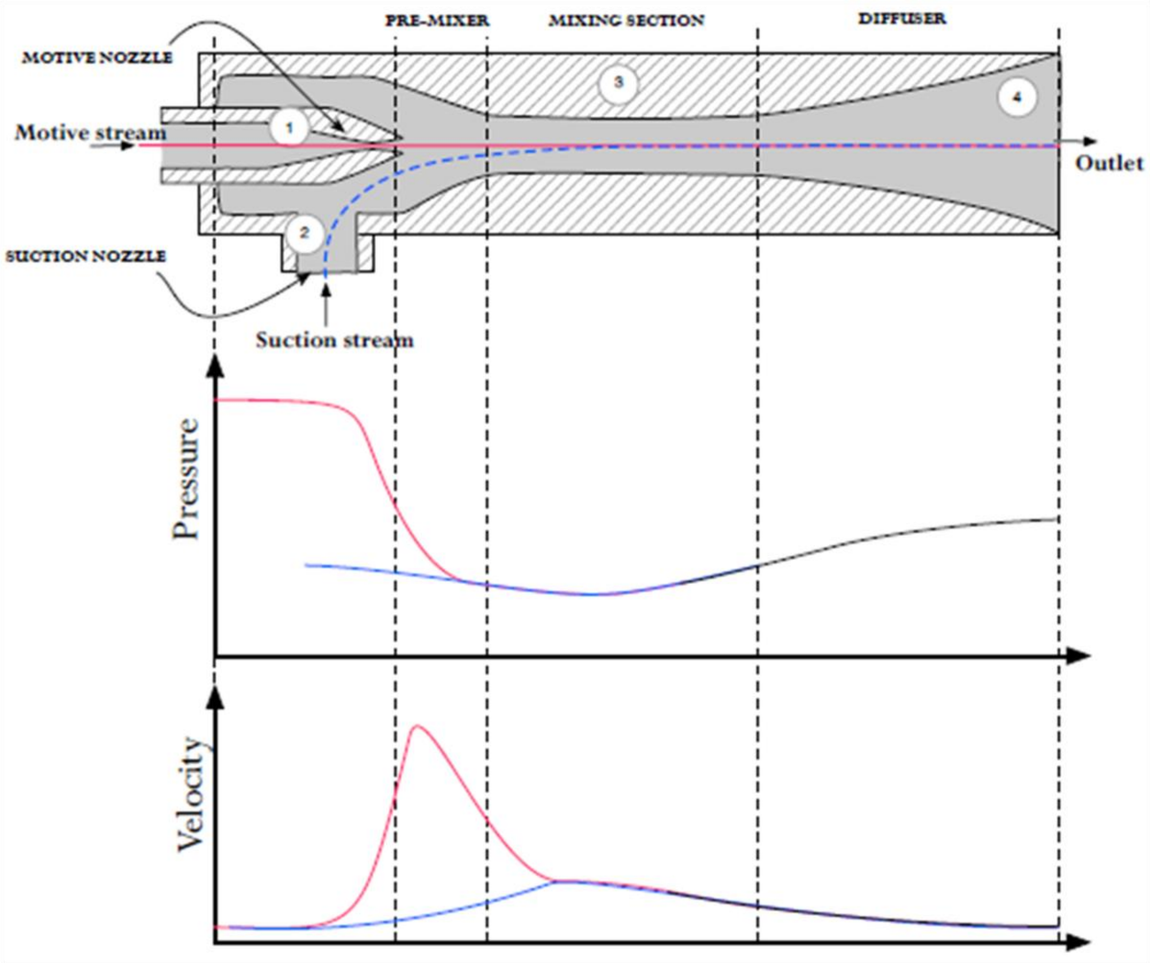


Fig.6: Ejector principle performance along with pressure and velocity profiles

Then, the motive flow exits the motive nozzle with high velocity and high kinetic energy. The motive and suction flows are mixed in the pre-mixer and mixing section (in the zone 3), where the flows exchange momentum. As the fluid is accelerated, a low pressure section is consider in the mixing section. Due to the low pressure in this section, the vapour at the suction accumulator is continuously entrained into the ejector (in the zone 2). Then, the diffuser converts the kinetic energy into pressure energy (in the zone 4).

Therefore, the ejector works as a motive stream driven fluid pump which entrains and increases the pressure of the secondary flow.

6.2. Ejector performance

Due to the different fluid dynamical process that occurs inside the ejector, such as friction, turbulence generation, shock waves... make the ejector performance distances from an ideal process. Because of this, the efficiency of ejector is considered as a function of the sum of all irreversibility that occur inside the ejector in a specific operation conditions.

In this case, the test facility is a two-phase ejector refrigeration system, so there are different degrees of freedom for each boundary condition:

- **Motive nozzle:** Pressure and temperature.
- **Suction nozzle:** Pressure, steam quality and temperature.
- **Outlet:** Pressure.

So, there are two independent inlet conditions, but a precisely defined operating condition lies in five variable parameters. Due to this, the ejector efficiency description, mapping and optimization are a very hard and complicated task.

According to (S. Elbel ,2007), based on the first thermodynamic law the ejector efficiency can be seen as the comparison between the expansion work recovered to the maximum expansion work recovery potential by the ejector, as it can see in the following equation:

$$\eta = \frac{W_{REC}}{W_{REC\ MAX}}$$

So, there are different operational points that it is necessary to evaluate, as it can be seen in the next figure, where the maximum work recovery possible is the difference between the enthalpies of the state A and B. However, the minimum work necessary to compress the suction mass flow is shown in the states C and D.

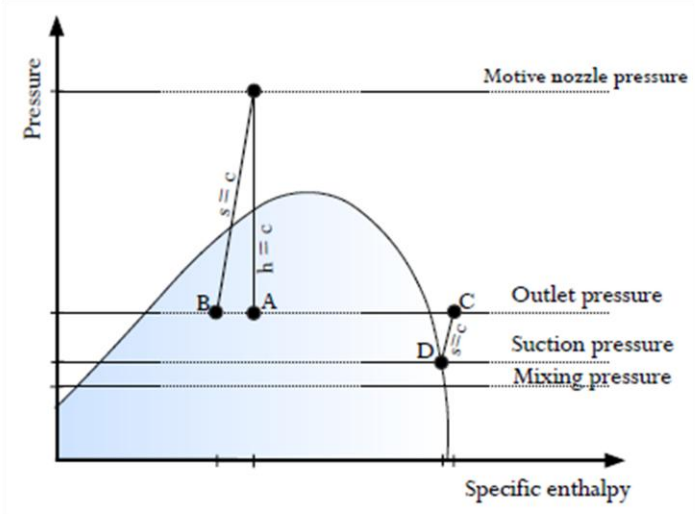


Fig. 7: Pressure&Enthalpy diagram
(S. Elbel, 2007)

On the one hand, the maximum expansion work recovered by the ejector can be calculated as:

$$W_{REC\ MAX} = \dot{m}_{MO} \int_{s_A}^{s_B} T_{diff.(out)} ds$$

Since the pressures are equals at the point A and B this equation can be written as:

$$W_{REC\ MAX} = \dot{m}_{MO}(h_B - h_A)$$

Using this equation in the previous equation:

$$vdP = dh - Tds = 0 \ \ (*)$$

On the other hand, the expansion work recovery potential by the ejector can be calculated as:

$$W_{REC} = \dot{m}_{SN} \int_{P_A}^{P_B} v(P) dP$$

It can be taken the assumption of isentropic compression between the points C and D, as it can be seen in the figure shown before. Also, using the equation seen above(*), the expansion work recovery potential can be represented as:

$$W_{REC} = \dot{m}_{SN}(h_C - h_D)$$

Therefore, the ejector efficiency can be represented as:

$$\eta = \Omega \, . \frac{h_C - h_D}{h_A - h_B}$$

representing Ω as the mass entrainment ratio of the ejector that is defined as the ratio of the suction mass flow rate($\dot{m}_{SN}$) to the motive mass flow rate($\dot{m}_{MO}$) and it is calculated as:

$$\Omega = \frac{\dot{m}_{SN}}{\dot{m}_{MO}}$$

Hence, the ejector efficiency can be estimated by means of parameters that can be obtained with high certainty from external measurements of temperature and pressure.

However, the ejector efficiency defined previously can not provide any information about the irreversibility of the process produced in the different section of the ejector. Indeed, if it can be observed the information considering the local flow profiles, it is possible to realize the irreversibility process that occurs in the ejector more extensively. According to (Banasiak et.al., 2014), it can be approached a profile using the sum of the relative increase of the entropy rate in each part of the ejector. Doing a entropy balance in the ejector, it can be calculated the increase of the entropy rate taking on that the ejector works adiabatically as:

$$\Delta\dot{S}_{Ej} = \dot{S}_{Ej.out} - \Sigma\dot{S}_{Ej.in}$$

being $\Delta\dot{S}_{Ej}$ the entropy rate at the outlet, and being $\Sigma\dot{S}_{Ej.in}$ the entropy rate provided by the motive and the suction entropy rate inlet of the ejector. So, the cumulative relative increase of the entropy rate could be defined as:

$$\varepsilon_n = \frac{\Delta\dot{S}_x}{\Delta\dot{S}_{Ej}}$$

Being n any discrete section of the ejector, and the parameter ε_n represents the local degree of the entropy increase along the different regions of the ejector. So, the parameters to analyse the ejector behaviour are the cumulative relative increase of entropy rate and the ejector efficiency.

7. Experimental test

7.1. Test facility description

The test facility of R744 ejector refrigeration system is divided into three different modules: the R744 unit, the glycol unit and the electrical cabinet. It consists of the R744 unit, which is connected with two glycol loops in order to providing cooling and heat to the gas coolers and evaporators, respectively. In the following picture , it can see the R744 unit on the left hand and the glycol unit on the right hand.

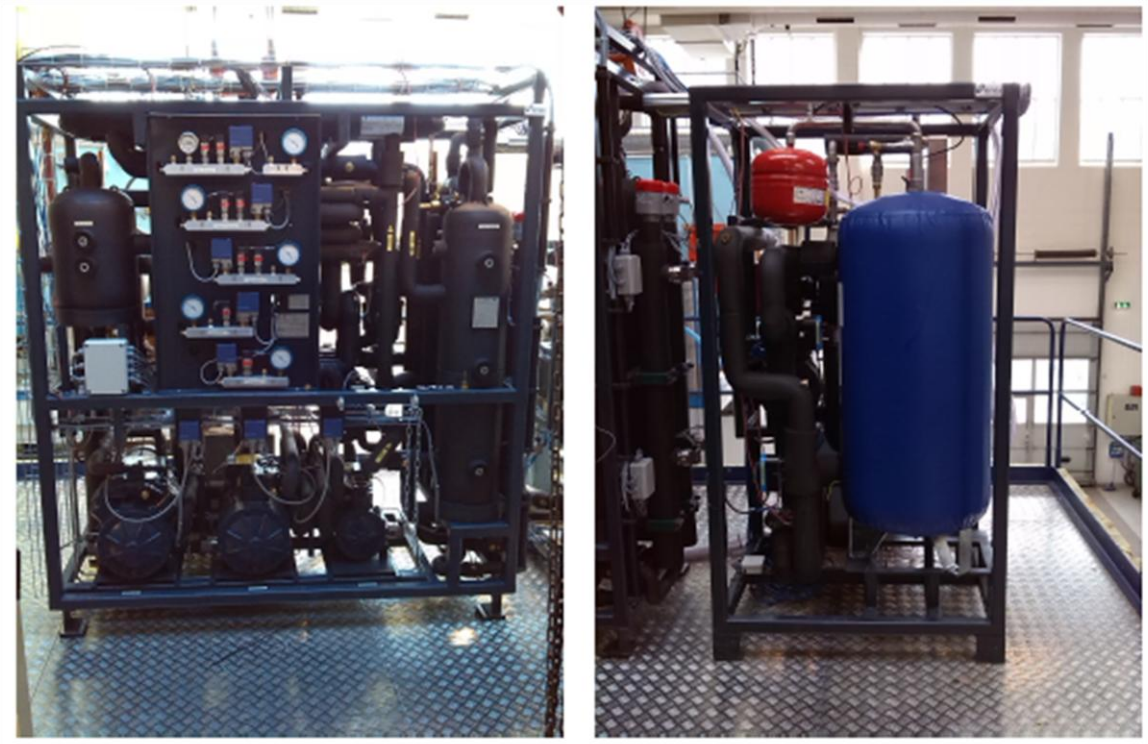


Fig. 8: The R744 unit and the glycol unit

Moreover, the second glycol loop could provide extracool to the test facility by the cooler located at the laboratory basement, as it can see in the following picture. This low temperature loop is used in order to decrease the motive nozzle inlet ejector temperature when the high temperature loop can not provide lower temperatures for the test facility.

Fig. 9: The auxiliary glycol cooler

As it can be seen below in the simplified cycle diagram of the test facility, there are three compressors with different power capacity operating with two different pressure levels. The MT compressor located in the low pressure side is connected to the suction accumulation tank, while the parallel compressors are connected to the liquid receiver and they are working in a lower pressure range. When just the MT compressor is working, the flash valve controls the difference pressure between the suction accumulation tank and the liquid receiver. Then, if the different boundary conditions of the ejector are set, the flash valve keeps the desired pressure lift.

Moreover, as it can see in the cycle diagram, there is a expansion valve working in parallel with the ejectors. This expansion valve controls pressure differences when the test is working and it ensures the test facility avoiding high pressures during operation.

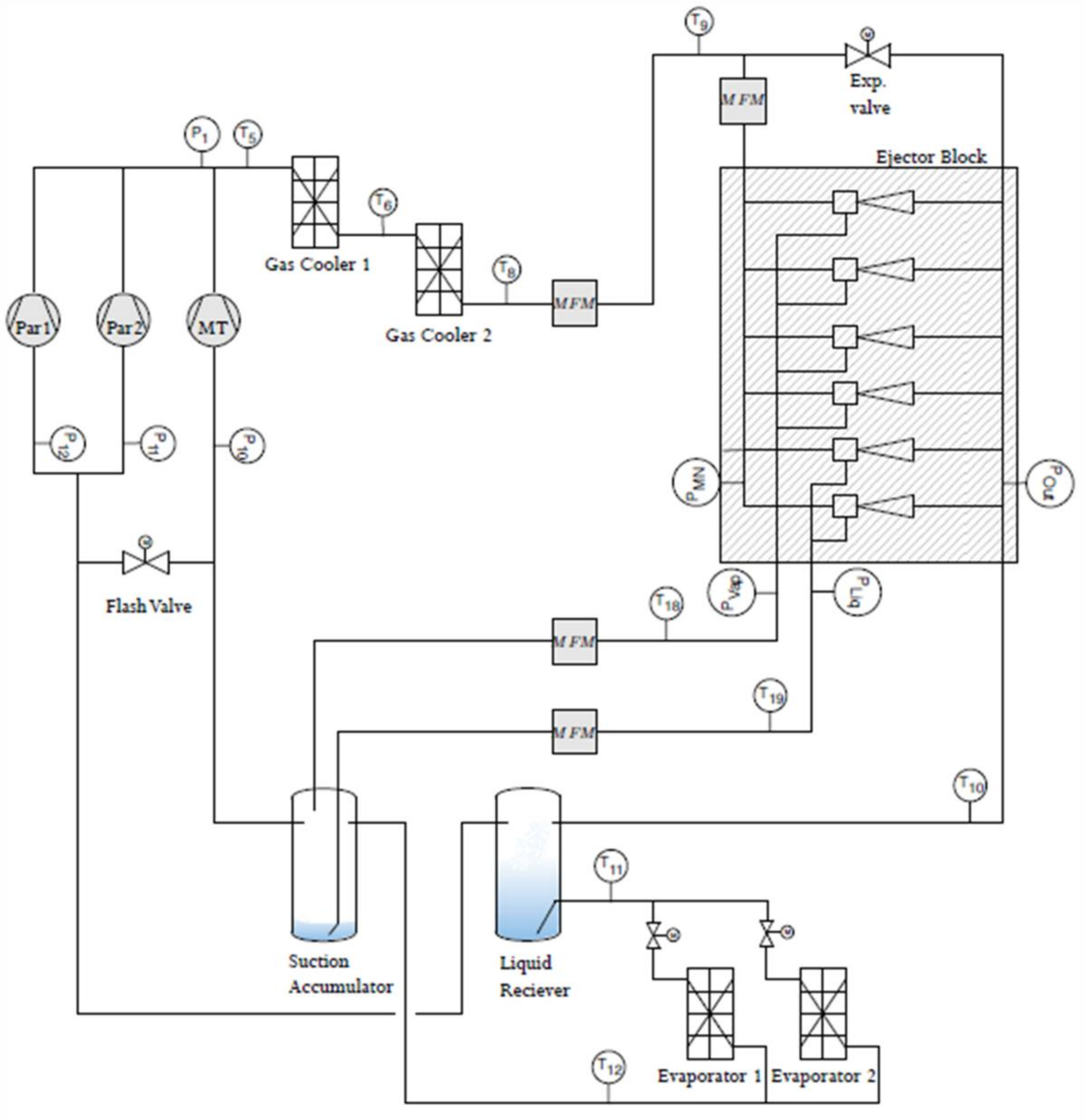


Fig.10: The test facility diagram cycle

Besides of that, both the ejector vapour and liquid suction manifold are connected to the suction tank located downstream from the evaporators. The objective of the evaporators is actually for transporting liquid from the suction tank to the liquid receiver, which introduces another energy saving potential in the refrigeration cycle. This energy saving potential is the possibility to working with the evaporators in flooded mode limiting the superheat to a minimum for compressor security. However, this superheat would be a energy loss in the standard refrigeration cycle actually.

Otherwise, there are two auxiliary loops in order to providing and rejecting heat to the gas coolers and evaporators, as it can see in the next diagram. The installation uses one glycol loop for remove heat from gas cooler 1 and for provide the same heat for the evaporators too. Also, heat can be provided to the evaporators by means of an electrical heater located in the glycol tank. Besides, the glycol used in the gas cooler 1 can be precooled in a internal water loop in order to eliminate the heat excess produced by the compressors. In addition, the second gas cooler is connected with a external low temperature glycol loop located in the laboratory basement, as it has been explained before.

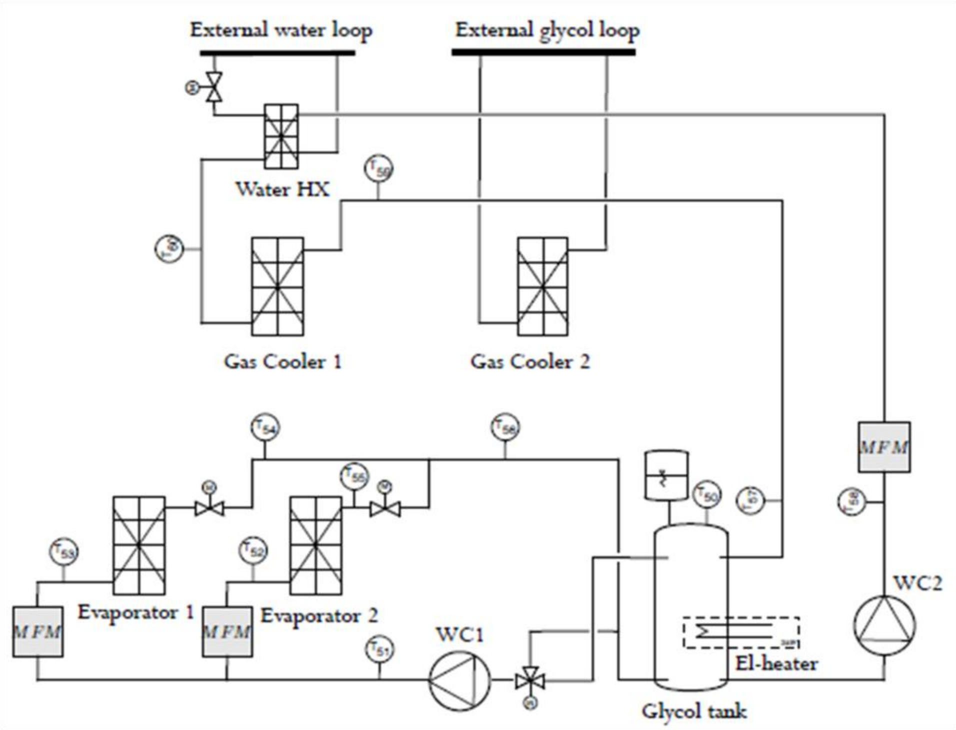


Fig. 11: The glycol loop diagram

The main components of the test facility are the compressors, the ejectors, the gas coolers, the liquid receiver and suction accumulator tank, the evaporators and the glycol circulation pumps.

- Compressors: The installation contains three compressor with different sizes produced by Dorin. The main compressor is the MT compressor: Dorin CD1400H and the parallel compressors are the model Dorin CD1000H and the model Dorin CD360H.

- Ejectors: The purpose of the ejector's design is that the ejector can provide the maximum flexibility in adapting to different operating conditions produced in the commercial refrigeration system. Although this research is just working with one ejector, the rig is equipped with four ejectors scaled in a linear combination in order to change the ejector capacity in presence of different operation points. Also, the ejectors are mounted in a single standard housing because of the complexity reduction of the installation and maintainability of the ejectors in the rig. All the ejectors have the same dimensions doing possible the interchange or replace any ejector. The housing has one motive manifold and one outlet manifold common for all ejectors. The ejectors are controlled by solenoid valves opening and closing the ejector access to the common manifold allowing the ejectors to work in parallel or individual mode. In addition, the ejectors are equipped with a suction internal check valve to avoid back flow from the outlet manifold when the ejector is not working.

- Gas coolers: There are two gas cooler of the plate heat exchanger class produced by KAORI. The first gas cooler is 30 plate and the second gas cooler is 20 plate.

- Liquid receiver and suction accumulator tank: Two pressure vessels whose capacity is 39 litres. The pressure vessels are manufactured by Frigomec.

- Evaporators: There are two evaporators of the plate heat exchanger class produced by KAORI. The first evaporator is 30 plate and the second evaporator is 20 plate.

- Glycol circulation pumps: There are two MANGA3 circulation pumps produced by Grundfos.

Besides of that, the installation is equipped with several temperature and pressure sensors, as it can see in the cycle diagram of the test facility. All sensors of the test facility are connected by means of the Danfoss controller, where all the information received from the ejectors is used in order to monitoring, controlling and safeguarding the system. However, there are sensors more important than others to test the ejectors and monitoring the refrigeration system performance.

The next table shows the different instrumentation used and the accuracy stated in the product description of each component taken from datasheet:

Class	Brand	Product ID	Type	Location	Accuracy
Pressure	Danfoss	AKS 2050	Piezoelectric	R744	±0.3%
Mass flow	Rheonik	RHM06	Coriolis	R744	±0.2%
Mass flow	Rheonik	RHM15	Coriolis	Glycol	±0.2%
Temperature	Danfoss	AKS 21 A	PT1000	Glycol & R744	±(0.3 + 0.005xT)

Table 1: Measurement devices in the test facility with the respective accuracy

Then, it is necessary to explain how works each kind of sensor in the test facility, as it can see below:

- *Pressure sensor* is a ratiometric pressure transmitter which converts the measured pressure into a linear voltage output signal. The pressure sensor has 1.013 bar as a pressure reference and it uses a sealed gauge measuring mainly. According to the different position of the pressure sensor in the system, their ranges can vary from 0 to 160 bar abs, or from 0 to 100 bar abs.

- *Mass flow meters* are the coriolis kind, measuring the phase that the flow pass through a vibrating curved tube, so they are very sensitive. Due to that, the mass flow meters are located on concrete blocks separate from the rest of the installation and connected with the rest of the rig by flexible reinforced wires. The range of the phase determined between the inlet and outlet of the tube becomes a function of the mass flow rate.

- *Temperature sensor* consists of a platinum component that varies its electrical resistance according to the temperature, and in this case, PT1000 gives a resistance of 1000Ω at 0 ºC.

7.2. Information acquisition and processing

As it has been explained before, all the sensors are connected to the Danfoss control unit. Also, there is a software running on the operator computer named *Danfoss Minilog data system,* which received the information instantly transmitted by the controller. This program allows to change different set points. Besides, it uses graphical representations of the fundamental performance parameters, so it is easier to monitoring several parameters for the operator at the same time, as it can see in the next diagram.

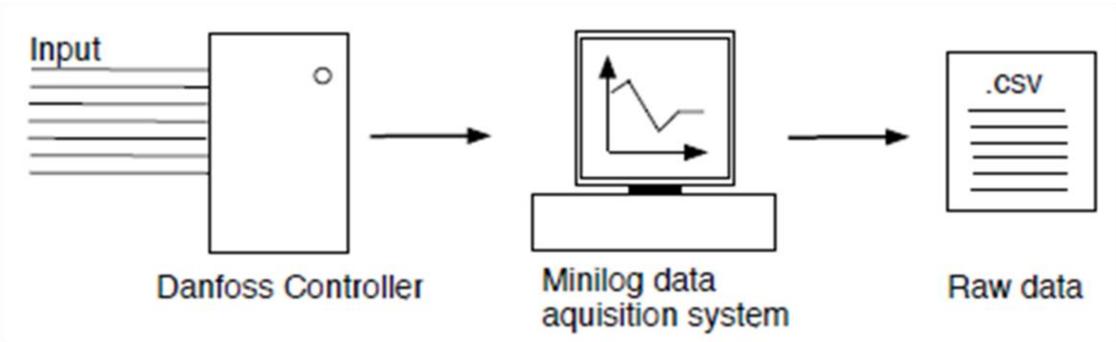


Fig. 12: Data collecting and monitoring process

Then, when a given test condition is determined and the steady state is maintained during 6 minutes, the test point is recorded. The duration of the recording was set to 6 minutes in order to minimize the influence of minor oscillations and to ensure the obtained information correspond to the determined test point. All the recorded information from the *Danfoss Minilog system* is exported to *.csv* files and imported in a processing Excel spreadsheet created for this purpose specifically. The spreadsheet estimates the mass entrainment ratio, the efficiency and the pressure lift, along both types of uncertainties: type A and type B. All the processing process is shown in the next diagram.

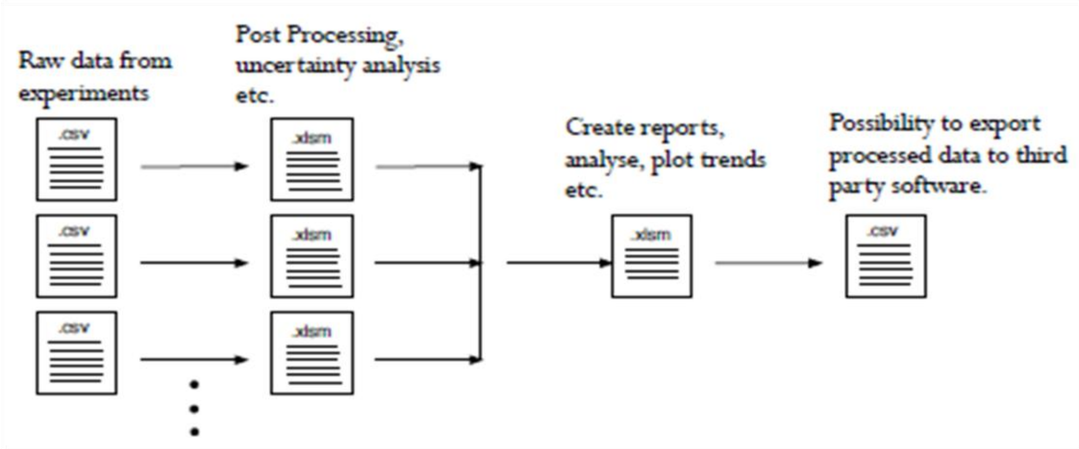


Fig. 13: Data exporting process

7.3. Uncertainty analysis of the obtained information

The result of all measurements obtained in the test facility is only an estimation of the real values because of the sensor's accuracy or the standard deviation for the series of obtained measurements. Hence, the obtained results might be considered complete when they are attached of the extract of its uncertainty. In all the experimental work, the method in order to determine the process uncertainty was selected from the *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results (1994).* As it has been explained before, there are two different categories in the experimental uncertainty:

- Type A: The uncertainty evaluation of a series of observations by the statistical analysis.
- Type B: The uncertainty evaluation of a series of observations by means other than the statistical methods.

The difference between these two kinds of determine the uncertainties of the process are very important. The kind uncertainty A is based on any statistical method for treating data, such as taking the standard deviation of a series of independent observations. However, the kind uncertainty B is based on scientific judgement by means of all relevant information available to the operator, like using calibration reports or manufacturers references.

On the one hand, the type A error denoted is defined as the standard deviation of the obtained measurements in the phase of six minutes in a specific test point condition. The sample is determined as:

$$x_i = \bar{X}_i = \frac{1}{n}\sum_{k=1}^{n} X_{i,k},$$

So, the standard deviation of the type A is:

$$u_A = s(\bar{X}_i) = \left(\frac{1}{n(n-1)} \sum_{k=1}^{n} \left(X_{i,k} - \bar{X}_i \right)^2 \right)^{\frac{1}{2}}$$

On the other hand, the uncertainty type B is calculated by the sensor accuracy from its manufacturers references. The sensor accuracy is used to establish upper and lower limits for the obtained measurements. The probability that all values obtained are in the determined range is assumed to be 100%. The probability is calculated by a rectangular distribution, so it is equally probable that the obtained values will be inside the limited range. Then, the best way in order to estimate the quantity according to Taylor N.B. (1994) is

$$x_i = \frac{(a_+ + a_-)}{2}$$

Being the uncertainty calculated as

$$u_B = \frac{a}{\sqrt{3}}$$

And

$$a = \frac{(a_+ - a_-)}{2}$$

The combined uncertainty is calculated as a function of the measured values by *the law of propagation of uncertainties* with uncertainty components estimated as standard deviations. The combined uncertainty is calculated by:

$$u_c = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 \cdot u_i^2(x) + \left(\frac{\partial f}{\partial y}\right)^2 \cdot u_i^2(y)}$$

Where the partial derivatives is

$$\frac{\partial f}{\partial x} = \frac{f(x+dx, y) - f(x,y)}{dx}$$

Thus, the combined uncertainty could be either the type A or type B can be related with the quantity x or y, which results in the combined uncertainty A and B, respectively. In the last equation, the covariance between the uncertainty of x and y is assumed to be zero.

Then, it is possible to investigate the difference between the uncertainty related to the steady state condition and the uncertainty related to the sensor's accuracy, that is to say, type A and type B, and it is concluded that the uncertainty related to the sensor's accuracy is more or equal than the uncertainty related to the steady state condition.

8. Research Objective and Performance Parameters

The objective of this thesis is to give a better understanding of the ejector performance by means of experimental analysis at different operation points. The control of the ejector refrigeration system gives a lot of information by means of different parameters, but the most important parameters are the following:

- The evaporation temperature(T_o): The study has been carried out for two possible temperatures of refrigeration, which are -3.2 and -8 degrees, because these are the commercial temperatures fundamentally.

- The motive nozzle inlet temperature (T_8): The ejector behaviour has been analysed for a wide range of temperatures between 10 and 37 degrees. In order to obtain the motive nozzle inlet temperatures down of 20 degrees, it was necessary to use the auxiliary low temperature loop.

- The discharge pressure(P_{GC}): The ejector performance has been analysed in different discharge pressures in order to obtain which are the pressures to achieve the highest COP or the highest efficiency.

- The receiver pressure(P_{REC}): The receiver pressure has the higher limit when the ejector can not send suction flow, and the lower limit depends on the evaporation temperature and the thermodynamic properties of the carbon dioxide. It was between 29 bar and 41 bar approximately.

- The pressure lift(ΔP): The pressure difference between the suction accumulator and the liquid receiver. The higher limit pressure difference depends on the test point that has been operated.

- The suction mass flow($\dot{m}_{SN}$): The mass flow sent through the ejector from the suction accumulator to the liquid receiver.

- The motive mass flow($\dot{m}_{MO}$): The mass flow sent through the ejector from the gas coolers into the liquid receiver.

Otherwise, it can see in the next table, all the set points which have been operated by the ejector refrigeration system in the test facility explained before. Due to the fact that the ejector can not achieve more difference pressure at the lower motive nozzle inlet temperatures of 17ºC, these test point have been measured only with the evaporation temperature of -8 degrees.

T_B (ºC)	P_{GC} = 55 bar	P_{GC} = 65 bar	P_{GC} = 75 bar	P_{GC} = 85 bar	P_{GC} = 95 bar
10	X	X			
13	X	X			
17	X	X			
20	X	X	X	X	
25		X	X	X	
27			X	X	
30			X	X	
33				X	
37					X

Table 2: Description of the conditions operated in the test facility at different motive nozzle inlet temperature and discharge pressure

Furthermore, in order to explain the ejector performance at different operating points, it is necessary to show several parameters, such as the pressure ratio, the mass entrainment ratio of the ejector and the ejector efficiency.

The pressure ratio(Π) is defined as the ratio of the ejector discharge pressure (P_{GC}) to the receiver pressure (P_{REC}):

$$\Pi = \frac{P_{GC}}{P_{REC}}$$

The mass entrainment ratio(Ω) of the ejector is defined as the ratio of the suction mass flow rate($\dot{m}_{SN}$) to the motive mass flow rate($\dot{m}_{MO}$):

$$\Omega = \frac{\dot{m}_{SN}}{\dot{m}_{MO}}$$

The ejector efficiency(η) is obtained of the definition stated by S. Elbel (2007), where is compared the expansion work recovered by the ejector to the maximum work recovery potential by the ejector.

$$\eta = \frac{W_{REC}}{W_{REC\ MAX}}$$

9. Results and Analisys

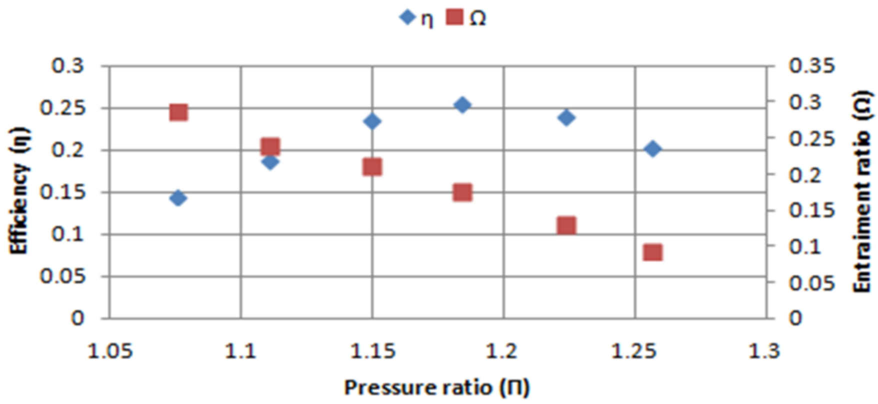
All the information obtained of the experimental test is detailed in the next table, as it has explained in the last chapter.

There are three main parameters of each test point in order to represent the different test points, which are the evaporation temperature(T_o), the motive nozzle inlet temperature (T_8) and the discharge pressure (P_{GC}). All the test points in the table have been analysed working in the test facility and the respective performance graphics can be found in the appendix. Also, it can see the specific information data obtained of each test point in the appendix.

Graphic number	T_o (ºC)	T_8 (ºC)	P_{GC} (bar)
1	-8	10	55
2	-8	10	65
3	-8	13	55
4	-8	13	65
5	-8	17	55
6	-3.2	17	55
7	-8	17	65
8	-8	20	55
9	-3.2	20	55
10	-8	20	65
11	-3.2	20	65
12	-8	20	75
13	-3.2	20	75
14	-8	20	85
15	-8	25	65
16	-3.2	25	65
17	-8	25	75
18	-3.2	25	75
19	-8	25	85
20	-8	27	75
21	-3.2	27	75
22	-8	27	85
23	-8	30	75
24	-3.2	30	75
25	-8	30	85
26	-8	33	85
27	-3.2	33	85
28	-8	37	95
29	-3.2	37	95

Table 3: Description of all the test points performed in the test facility

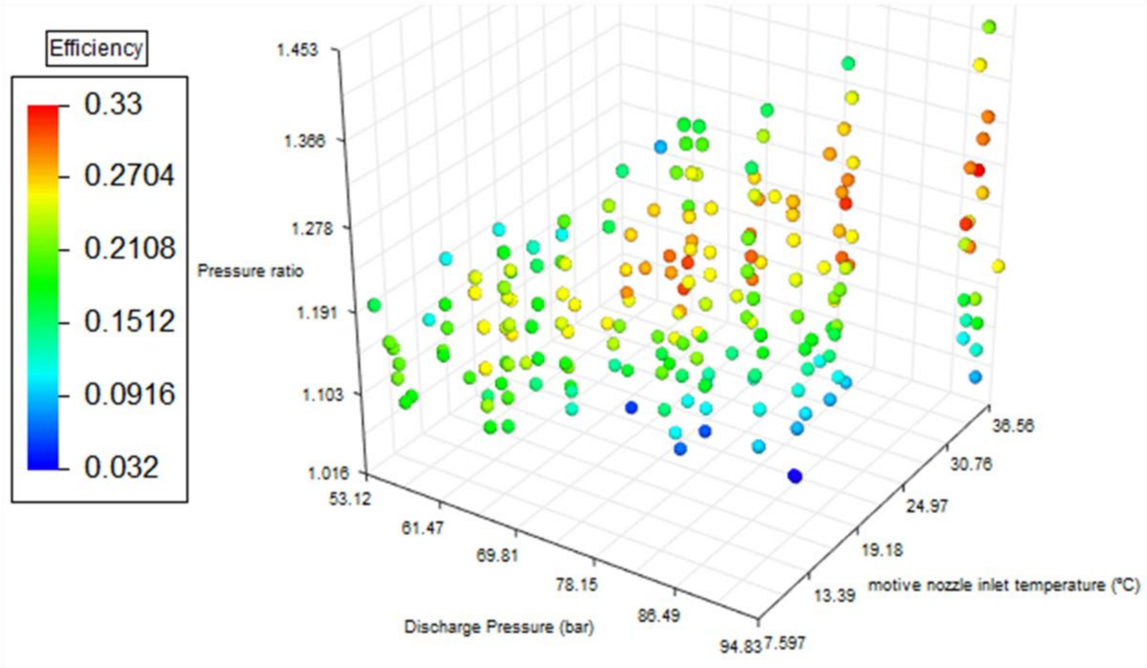
It can be emphasized, seeing the respective graphic of each test point, that the highest ejector efficiency depending on the motive nozzle inlet temperature is produced at different operation conditions. Also, the ejector efficiency is defined by a curve where the maximum is in the middle of the curve. This occurs because the friction losses generated into the ejector reach its minimum for the respective pressure lift depending on the inlet temperature. For example, as it can see in the following graphic:



Graphic 3: Test point performance with evaporation temperature of -8ºC, dicharge pressure of 65 bar and motive nozzle inlet temperature of 20ºC

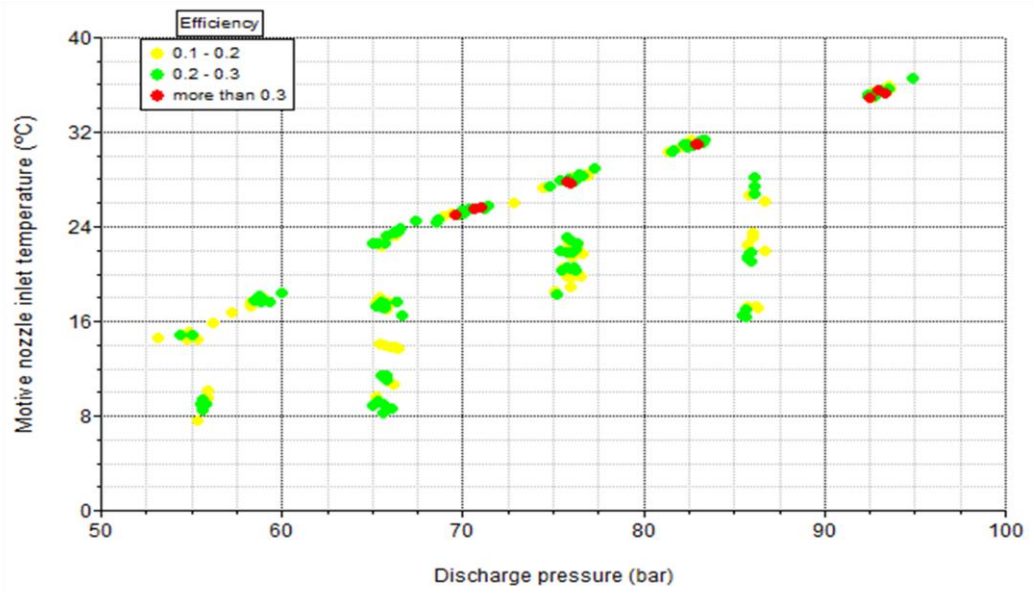
This test point is the number eleven and it is produced at the inlet temperature of 20ºC and the discharge pressure of 65 bar. The maximum efficiency is obtained at 1.18 bar of pressure ratio, and this pressure ratio corresponds to 5.25 bar of pressure lift. Besides of this, the entrainment ratio increases due to the decreasing vapour mass fraction at the ejector outlet which results in a higher suction flow rate. Also, the entrainment ratio increases as much as the lower the pressure ratio is, as it can be seen in the graphic 3. So, as the discharge pressure is steady at the different test point, it is concluded that the entrainment ratio decreases when the receiver pressure increases.

Otherwise, due to the fact that there are too parameters connected to the ejector performance is necessary to represent the results obtained testing the ejector refrigeration system in 3D dimension using the graphic software named *Teraplot*. This programme can represent in 3D dimensions, and the different axis are the pressure ratio (Π), the discharge pressure (P_{GC}) and the inlet motive nozzle temperature (T_8). Also, it has been represented the efficiency (η) of each test point by means of different ranges of colours.



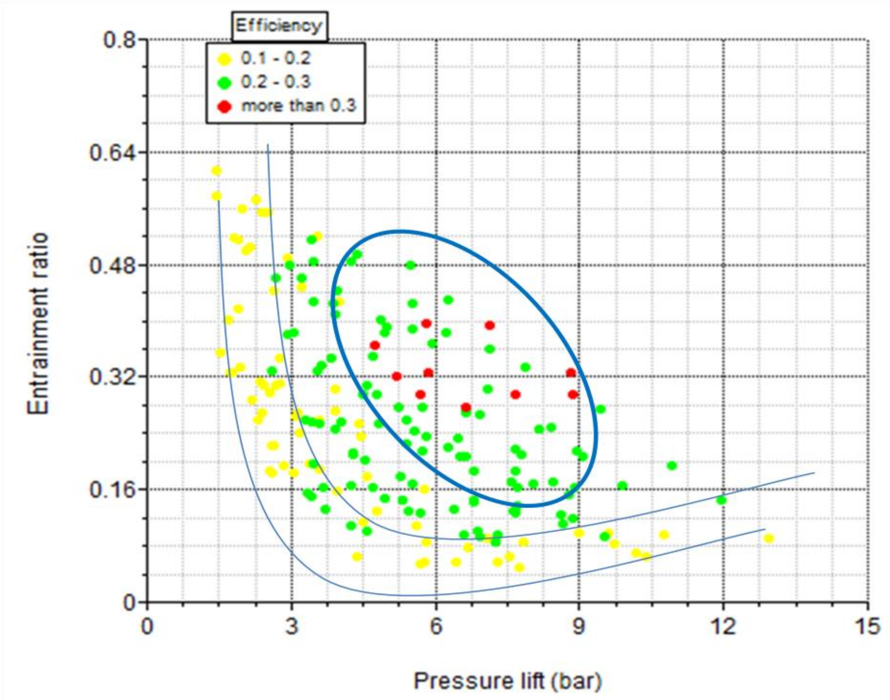
Graphic 4: 3D-Representation of alll test points

As it can see in the previous 3D graphic, there is a delimited range in which the ejector performance is working more efficient between the pressure ratio from 1.1 to 1.35, approximately. It can see in the next 2D graphics more clearly the dependence between the different parameters analysed.



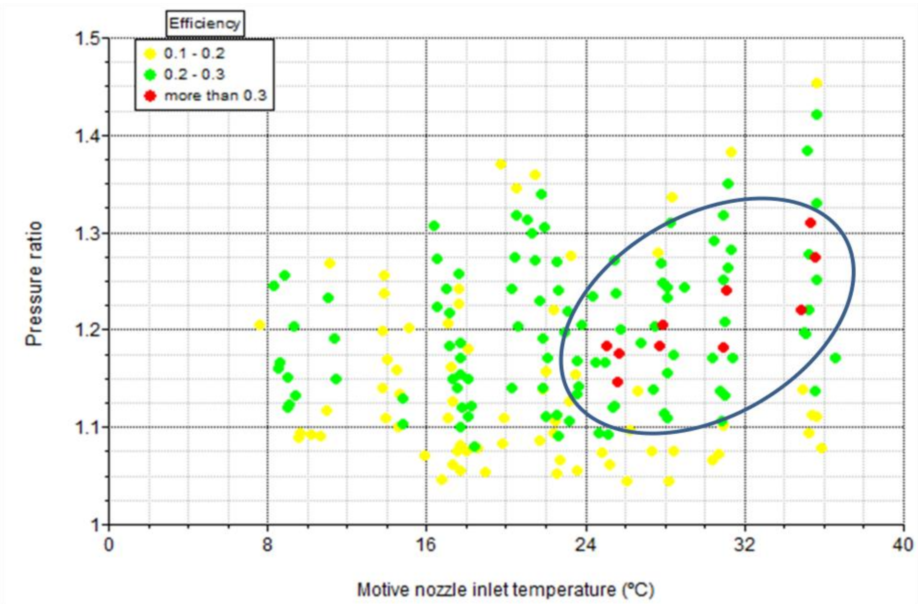
Graphic 5: 2D test point efficiency representation at different motive nozzle inlet temperature and discharge pressure

So, it can see in this graphic, the linear relation between the motive nozzle inlet temperature and the discharge pressure where the ejector has been working with high level of efficiency. Indeed, the graphic shows that the ejector performance is more efficient with higher inlet temperatures due to the fact that the ejector can supply more flow with higher pressure lifts and thus, the refrigeration system could reduce the energy consumption.



Graphic 6: 2D test point efficiency representation at different entrainment ratio and pressure lift

So, as it can see in the previous graphic, there is a range in which the ejector works with higher efficiency, as it has been explained previously. This range in defined with a pressure lift between 4 and 9 bar and with a entrainment ratio from 0.10 to 0.48, approximately.

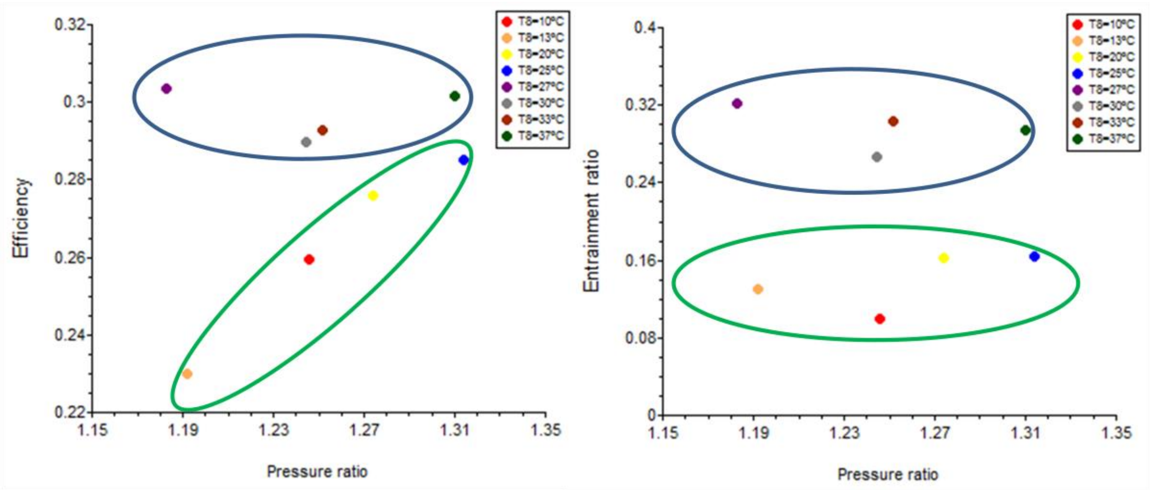


Graphic 7: 2D test point efficiency representation at different motive nozzle inlet temperature and pressure ratio

Thus, seeing this graphic, it is verified that the ejector performance is more efficient between the pressure ratio from 1.1 to 1.325, approximately.

Therefore, analysing the obtained results it has been defined a zone with determined operating conditions where the ejector has an increased efficient performance, and accordingly, a more efficient performance of the refrigeration system too.

However, it is necessary to emphasize that there is a big difference between the different operation conditions depending on each inlet temperature. So, the next graphic shows the most efficient operating point for each inlet temperature investigated with the evaporation temperature of -8ºC.



Graphic 8: 2D-Representation of highest efficient test points for each motive nozzle inlet temperature analyzed

It can see that working in high inlet temperatures the ejector efficiency is better than working in low temperatures. Therefore, it is shown that ejector perform more efficiently in warm climates than working the ejector in cold climates.

Also, it is showed the relation between the entrainment ratio for each inlet temperature, and it could be concluded that the operating points with higher entrainment ratio perform with the higher ejector efficiency. Besides, all the most efficient operating points are included in the more efficient pressure ratio range that it has been shown previously.

10. Discussion

First of all, it is necessary to explain the different specifications of this investigation. This investigation has been carried out in the university of NTNU in Trondheim, Norway. So, the test facility has been operated in a cold climate. Nonetheless, the purpose of work at different motive nozzle inlet temperature makes the possibility of extract conclusions about the best areas or climates in order to perform the ejector system efficiently.

Besides of that, it has to be emphasized that all temperatures and pressures at which the test facility has been operated have a slight error which has to be assumed before to extract conclusions about the results obtained. It can be found in the appendix the different data obtained and their respective graphic of each test point where it can be seen the accuracy of the results obtained compare to the test point searched.

Also, in this section it is going to compare the results obtained working in the descripted test facility with other recent investigations about the ejector refrigeration system with R744 as working fluid in order to extract conclusions about the ejector performance at different operation conditions.

On the one hand, the results show that the best efficiency can be found for pressure lifts between 3 to 12 bar, as it has been explained before. These results can be compared with the investigation entitled "*Multiejector concept for R744 supermarket refrigeration"*, carried out by Armin Hafner et. al. in 2014. In this work it can be seen that the highest efficiency obtained, which is about 10 to 27%, is working with pressure lifts between 2 to 6 bar. Although the pressure lift range investigated in our case is wider and the highest efficiency values are found in the pressure lift range between 4 to 9 bar, it could be conclude that there are matches between both studies because the efficiency values are similarly at pressure lifts between 2 to 6 bar , as it can see in the graphic 6. So, it is conclude that the highest ejector efficiency is reached working with pressure lifts between 4 to 9 bar.

On the other hand, the increase of the entrainment ratio is produced by an decrement of the pressure ratio, that is to say, the decrement of the receiver pressure, as it has been explained before analysing the graphic 3. Lucas and Koehler (2012) show that the entrainment ratio increases with increasing the high-side pressure. Therefore, it is proved that the entrainment ratio increases with decreasing the pressure lift in the system and the higher flow sent by the ejector, the higher energy saved in the system.

Otherwise, as it has be seen in the analysis of the graphic 7, the higher efficient ejector performance is working at the pressure ratio between pressure ratio from 1.1 to 1.325 and the highest efficiency is found at the pressure ratio of 1.275, approximately. However, observing the investigation carried out by Krystof Banasiak et. al. in 2014 entitled "*Test facility for a multi-ejector R744 refrigeration system*", it can be seen that the higher efficient ejector performance has been found working in the pressure ratio range between 1.14 to 1.29, and the highest efficiency is found at the pressure ratio of 1.23. Therefore, it can be conclude the matches between both studies and so, the pressure ratio range where the ejector efficiency is higher is from 1.1 to 1.325, and the highest efficiency at the pressure ratio around 1.275.

On the other hand, as it has been explained before, the higher motive nozzle inlet temperature, the higher ejector efficiency performance is. Also, the higher ambient temperature is, the higher ejector efficiency performance is. So, it is obvious that exits a relation between the increment of temperature and the ejector efficiency. According to (Elbel and Hrnjak 2008, Elbel 2011, Banasiak, Hafner et al. 2012, Lucas and Koehler 2012) R744 ejector might improve the system efficiency by up to 15% depending on the ambient temperature of the heat rejection device of the refrigeration system. Moreover, according to Armin Hafner et. al. (2012), the ejector system can improve the COP of the refrigeration system by up to 20% at high ambient temperature or high return temperature from the heat recovery system.

Hence, it can be concluded that depending on the ambient temperature, it would be better to perform the test facility at high or low discharge pressure according to the R744 characteristics. However, it is observed that the ejector refrigeration system works more efficiently at high ambient temperatures than working at low ambient temperature, and also, it is concluded that the ejector system works more efficiently at higher motive nozzle inlet temperatures than working at low motive nozzle inlet temperatures.

11. Conclusion

In this master thesis has been investigated experimentally the R744 ejector refrigeration system performance at different operation points in order to increase the knowledge of the ejector performance and at which motive nozzle inlet temperatures, pressure ratio or discharge pressure the ejector efficiency is the highest possible. This investigation has been done with only one ejector in a two-phase test facility and for two different evaporation temperatures of -8ºC and -3.2ºC.

The results obtained in this master thesis show that the ejector works more efficiently working with a pressure lift between 4 and 9 bar and with a entrainment ratio from 0.10 to 0.48, approximately. Also, it can be concluded that the ejector efficiency achieves the higher values working with the pressure ratio between 1.1 to 1.35, and the highest efficiency is found at the pressure ratio of 1.275, approximately. The ejector efficiency has achieved the maximum value that was around 35% with the pressure ratio named before. Furthermore, it can be concluded that working at high inlet temperatures the ejector efficiency is better than working at low temperatures. This is due to the fact that there is more energy saved by the ejector working at high temperatures because the expansion work is bigger than working at low temperatures. Therefore, it is concluded that ejector perform more efficiently in warm climates than working the ejector in cold climates.

Finally, in the present work, it has been analysed a two-phase ejector refrigeration system with R744 as a working fluid where it has been concluded the operation conditions where the ejector works more efficiently and at which temperatures the ejector efficiency is highest.

12. Further work

The purpose of the present work was to perform the ejector refrigeration system at different operation conditions in order to know at which points the efficiency can be higher. But, it is necessary to remind that all this work has been done working only with one ejector in the refrigeration system. So, a possible further work could be the possibility to work with more ejector and the possible combination of them. This work could be use to create a performance ejector map to know the best operation points at which the ejector refrigeration system should perform in the future.

On the other hand, in this work it has been investigated the test facility shown before, corresponding to a two-phase ejector refrigeration system. Hence, it would be a good further work to investigate the different type of ejector system and which have the highest efficient performance. Also, it could be figured out the relation between the operation parameters with the different ejectors systems in order to realize which ejector systems are better depending on the operation conditions.

Otherwise, it has been done this work in Trondheim, Norway, so in this case the ambient temperature has been steady in spite of the investigation performing the test facility at different motive nozzle inlet temperatures. Therefore, it would be a great further work to investigate the ejector performance at different ambient temperatures experimentally in order to know in which areas the ejector works more efficiently or what natural refrigerant would be better to use at the different climate areas.

In conclusion, there are many ways to continue the investigation of ejector refrigeration system using R744 as working fluid due to it is a very novel technology. Therefore, it is necessary to do an effort to reduce the Global warming and the environmental pollution, and this technology could be a possible solution to reduce both problems.

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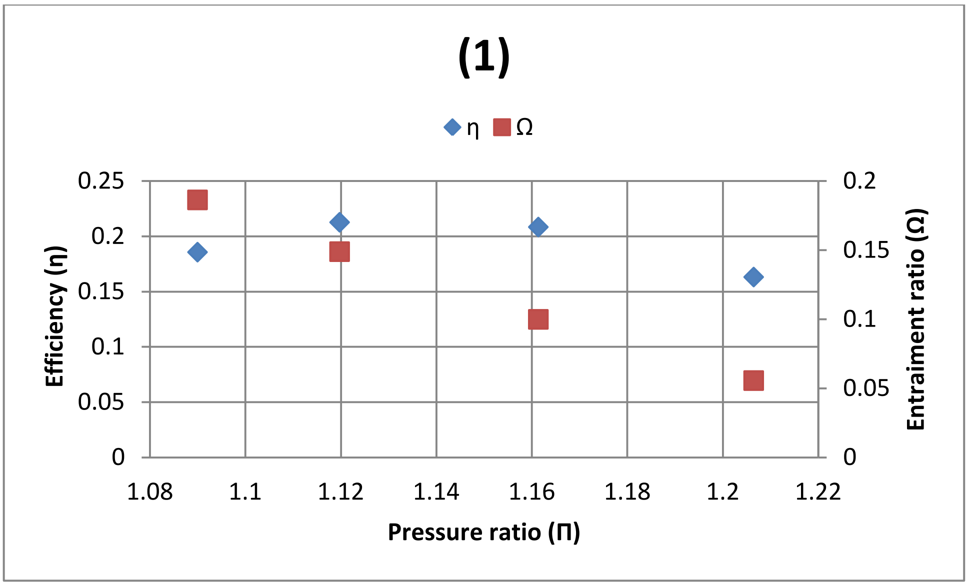
14. Appendix

Graphic number	T_o (ºC)	T_8 (ºC)	P_{GC} (bar)
1	-8	10	55
2	-8	10	65
3	-8	13	55
4	-8	13	65
5	-8	17	55
6	-3.2	17	55
7	-8	17	65
8	-8	20	55
9	-3.2	20	55
10	-8	20	65
11	-3.2	20	65
12	-8	20	75
13	-3.2	20	75
14	-8	20	85
15	-8	25	65
16	-3.2	25	65
17	-8	25	75
18	-3.2	25	75
19	-8	25	85
20	-8	27	75
21	-3.2	27	75
22	-8	27	85
23	-8	30	75
24	-3.2	30	75
25	-8	30	85
26	-8	33	85
27	-3.2	33	85
28	-8	37	95
29	-3.2	37	95

Table 3: Description of all the test points performed in the test facility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η Ω
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)
0.25
0.2
0.15
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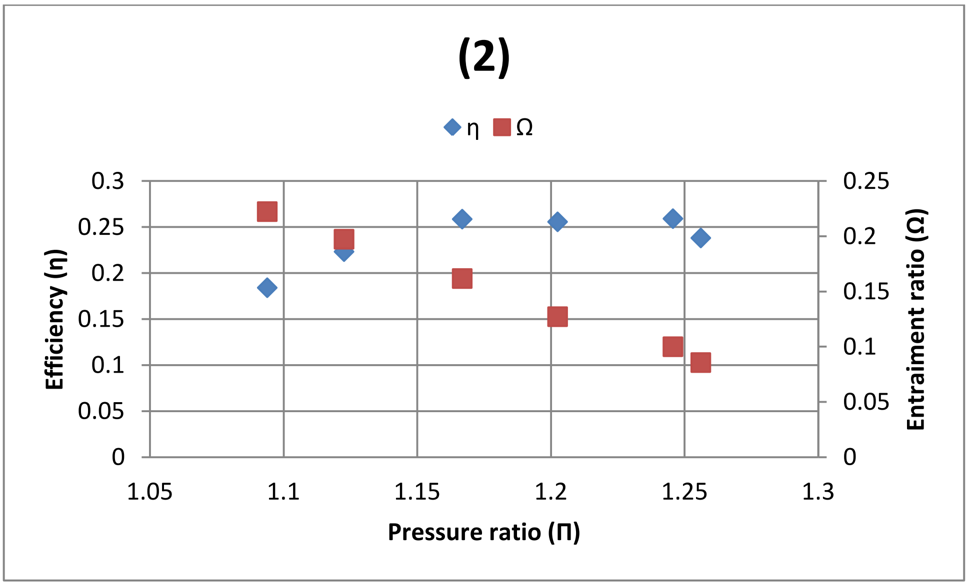
0.05
0
1.08
1.1
1.12
1.14
1.16
1.18
1.2
1.22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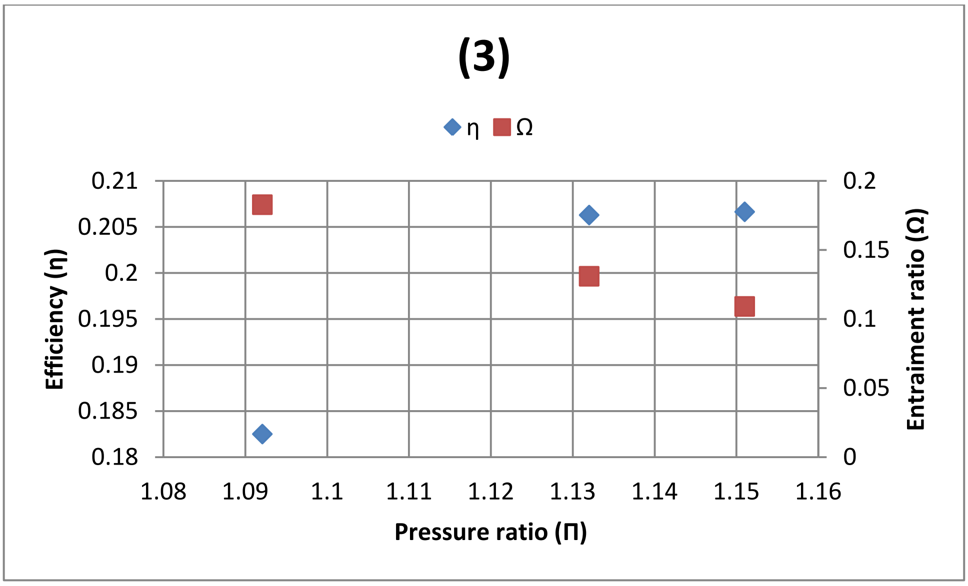
η Ω
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)
0.3
0.25
0.2
0.15
0.1
0.05
0
1.05
1.1
1.15
1.2
1.25
1.3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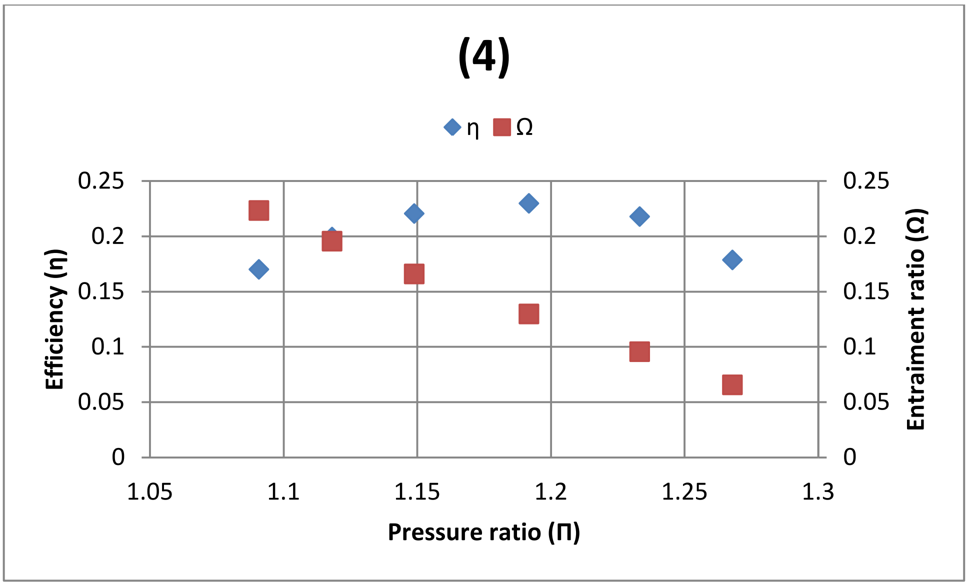
η Ω
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)
0.21
0.205
0.2
0.195
0.19
0.185
0.18
0.15
0.1
0.05
0
1.08
1.09
1.1
1.11
1.12
1.13
1.14
1.15
1.16



(4)
η Ω
0.25
0.2
0.15
0.1
0.05
0
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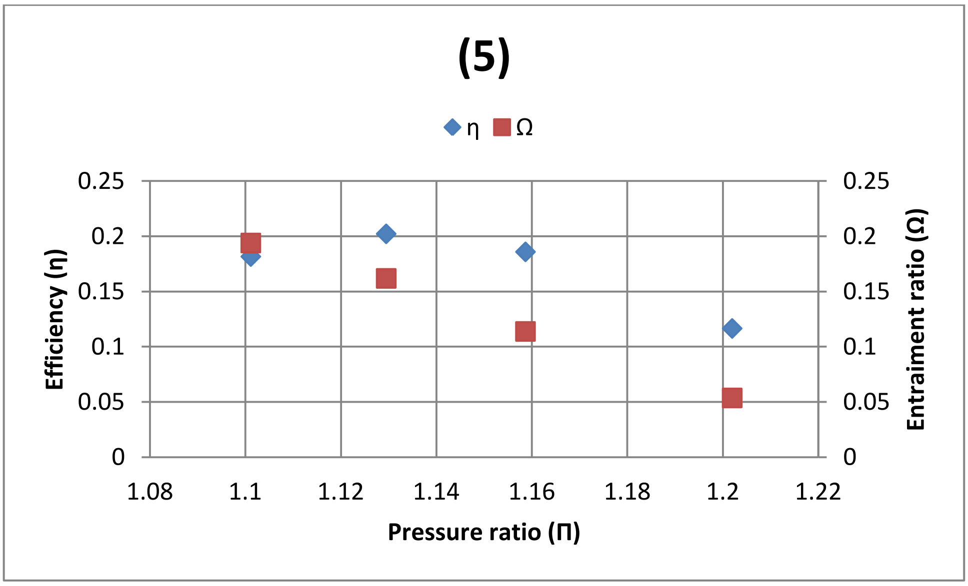
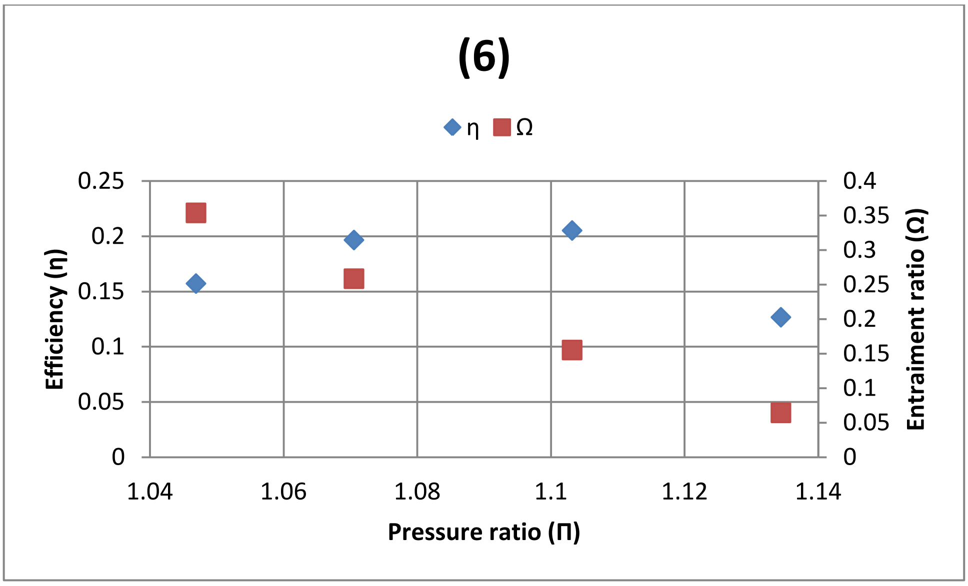
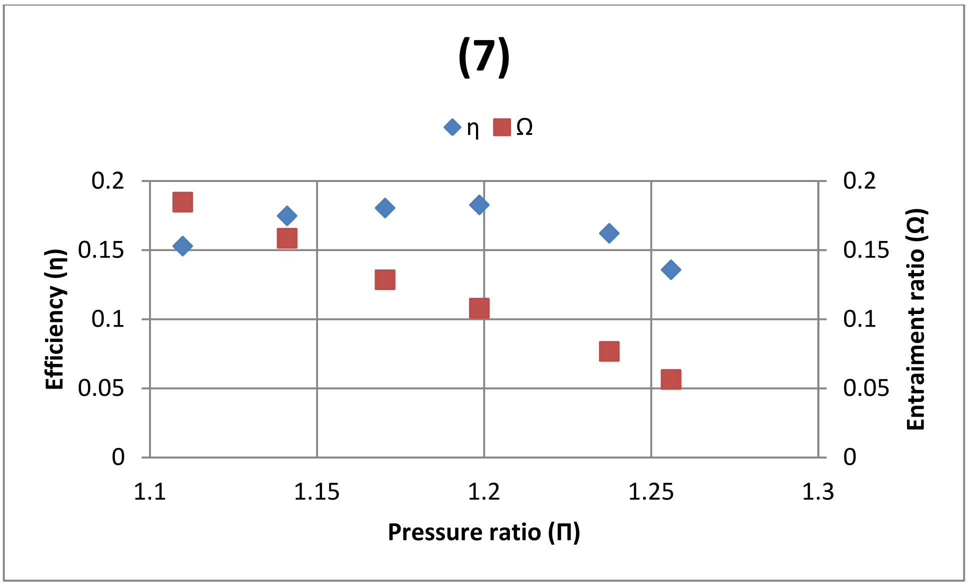
Entraiment ratio (Ω)
1.05
1.1
1.15
1.2
1.25
1.3
Pressure ratio (Π)



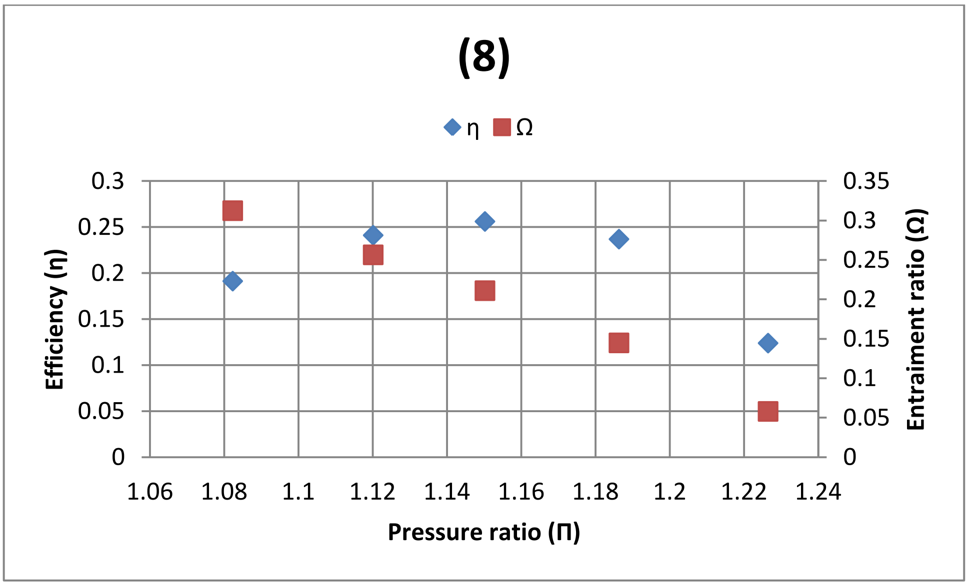
(5)
η Ω
0.25
0.2
0.15
0.1
0.05
0
Efficiency (η)
Entraiment ratio (Ω)
1.08
1.1
1.12
1.14
1.16
1.18
1.2
1.22
Pressure ratio (Π)



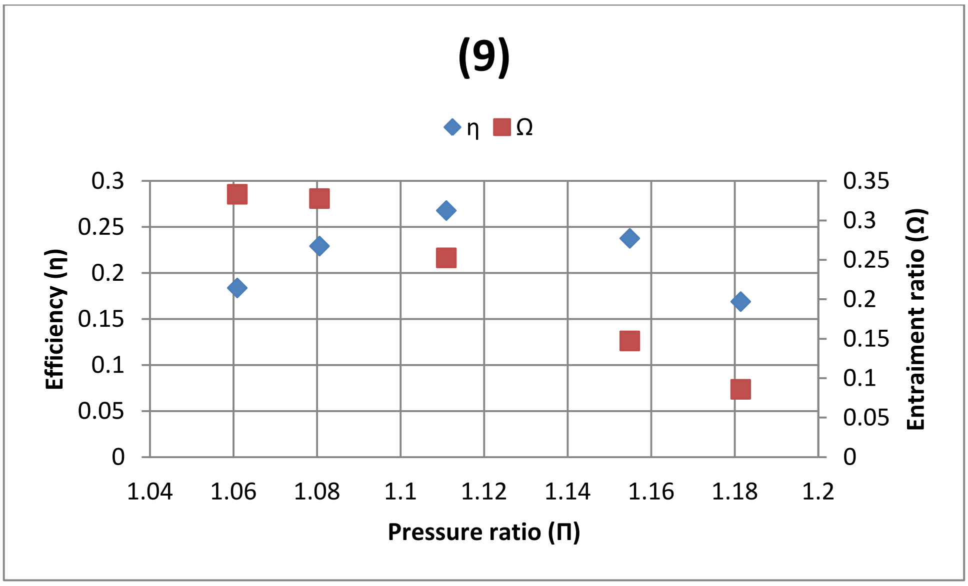
(6)
η Ω
0.25
0.2
0.15
0.1
0.05
0
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Efficiency (η)
Entraiment ratio (Ω)
1.04
1.06
1.08
1.1
1.12
1.14
Pressure ratio (Π)



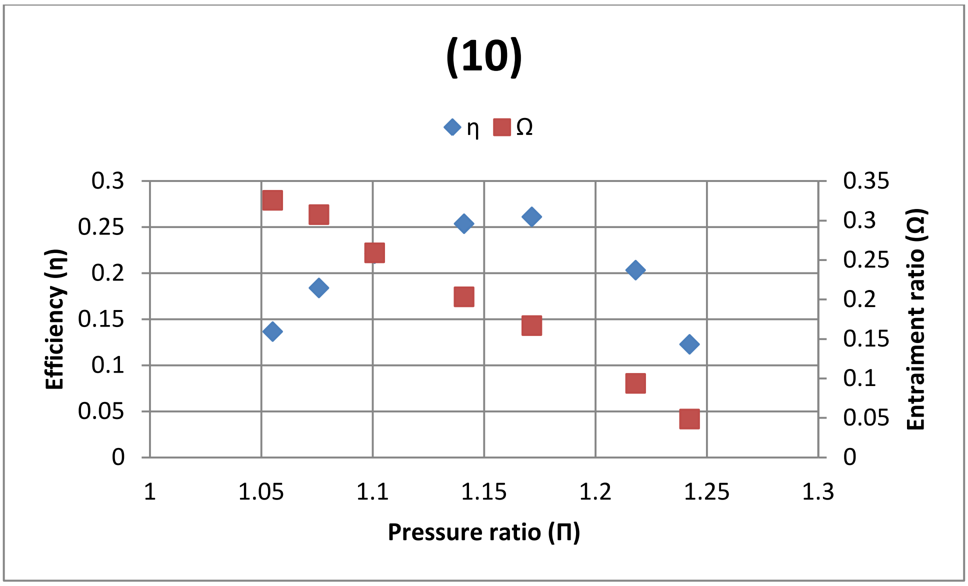
(7)
η Ω
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)
0 0.05 0.1 0.15 0.2
1.1 1.15 1.2 1.25 1.3

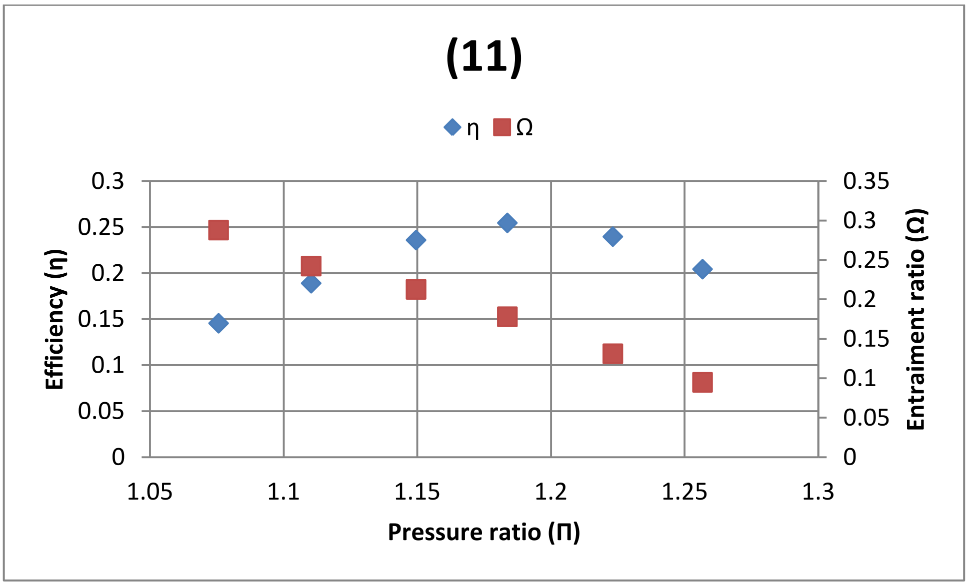


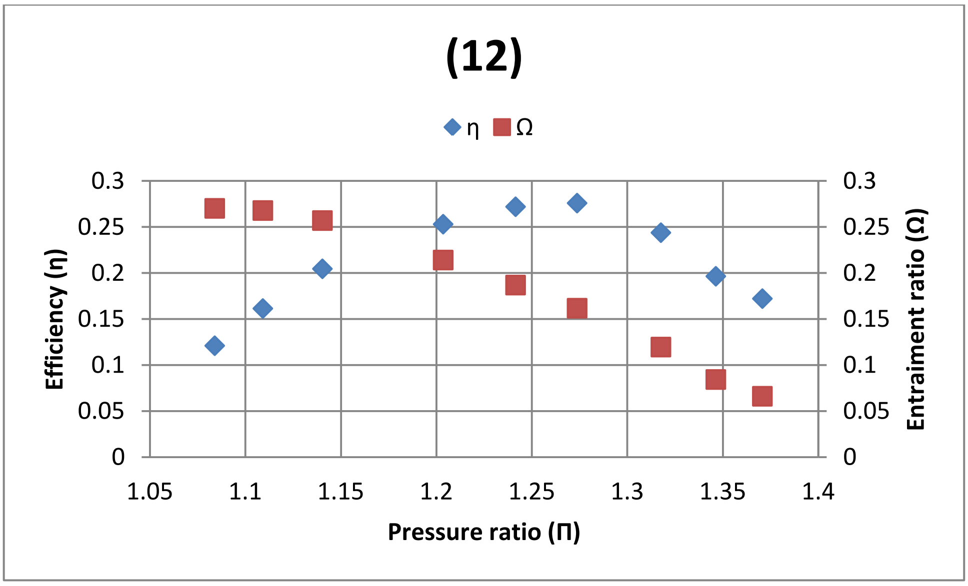
(8)
η Ω
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)
0 0.05 0.1 0.15 0.2 0.25 0.3
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
1.06 1.08 1.1 1.12 1.14 1.16 1.18 1.2 1.22 1.24

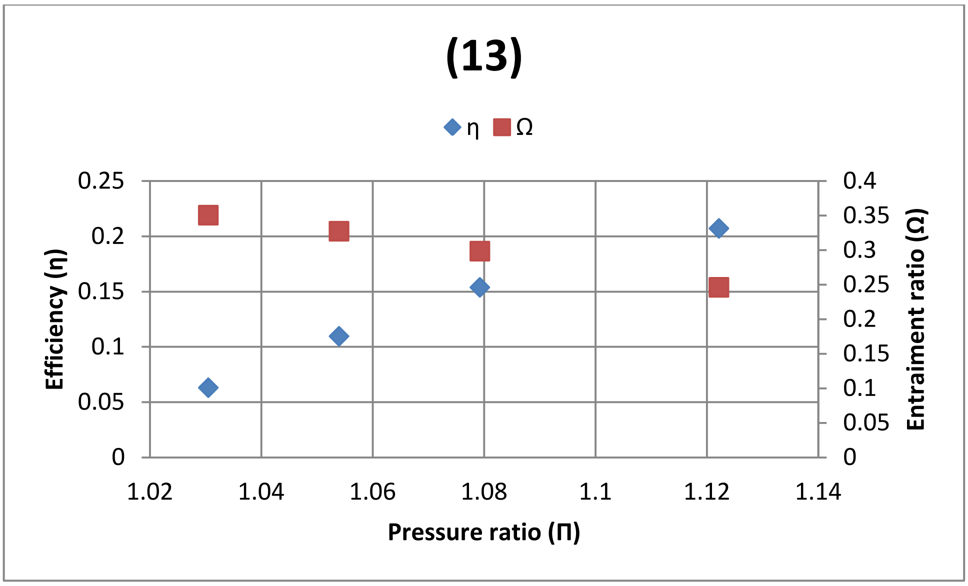


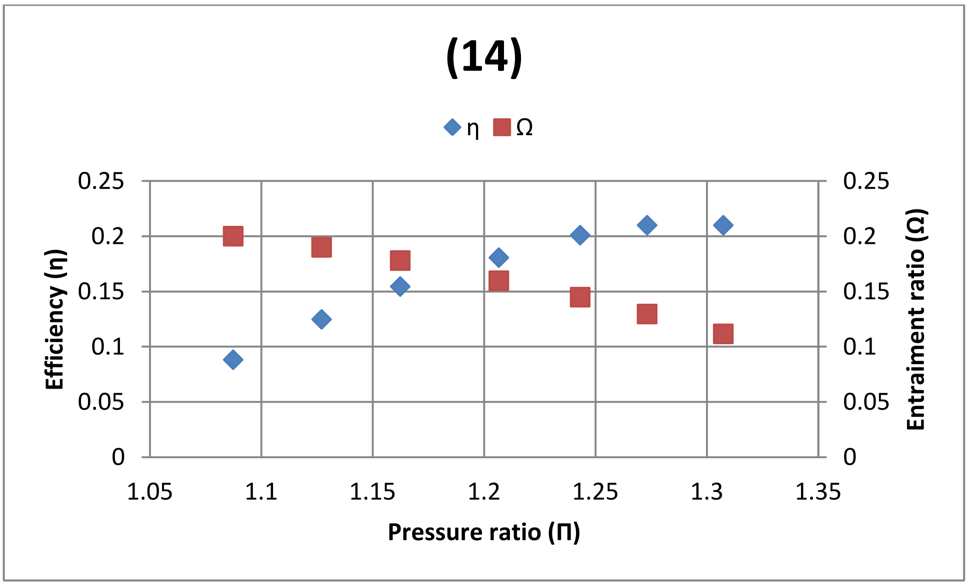
(9)
η Ω
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)
0 0.05 0.1 0.15 0.2 0.25 0.3
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
1.04 1.06 1.08 1.1 1.12 1.14 1.16 1.18 1.2


(10)
η Ω
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)
0.3
0.25
0.2
0.15
0.1
0.05
0
0.35
1
1.05
1.1
1.15
1.2
1.25
1.3


(11)
η Ω
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)
0.3
0.25
0.2
0.15
0.1
0.05
0
0.35
1.05
1.1
1.15
1.2
1.25
1.3


(12)
η Ω
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)
0.3
0.25
0.2
0.15
0.1
0.05
0
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4


(13)
η Ω
Efficiency (η)
0.25
0.2
0.15
0.1
0.05
0
Entraiment ratio (Ω)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1.02 1.04 1.06 1.08 1.1 1.12 1.14
Pressure ratio (Π)


(14)
η Ω
Efficiency (η)
0.25
0.2
0.15
0.1
0.05
0
Entraiment ratio (Ω)
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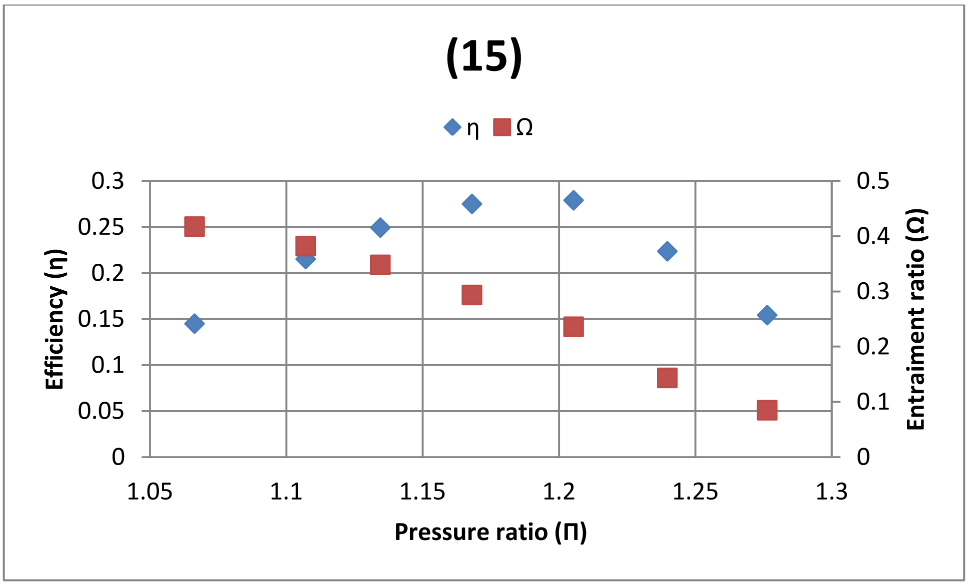
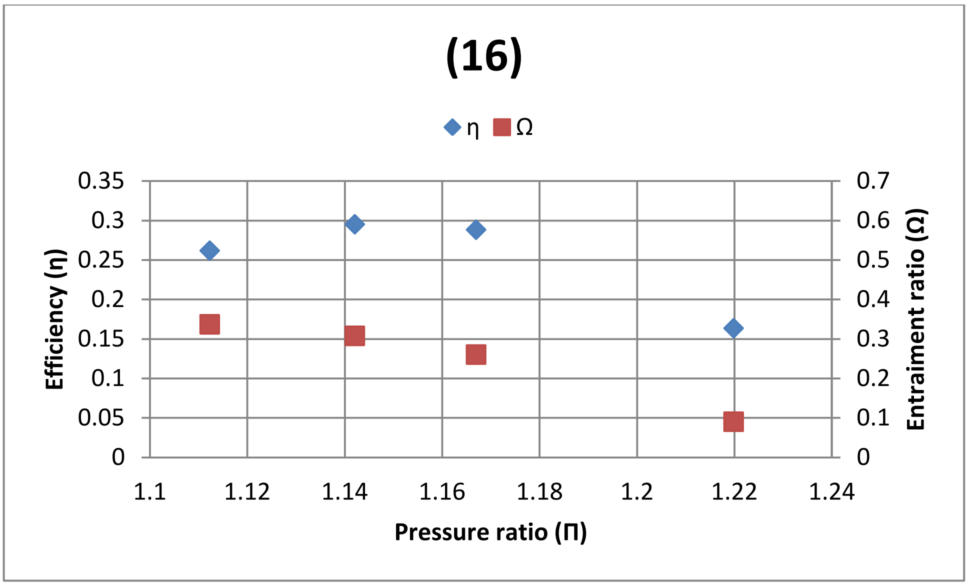
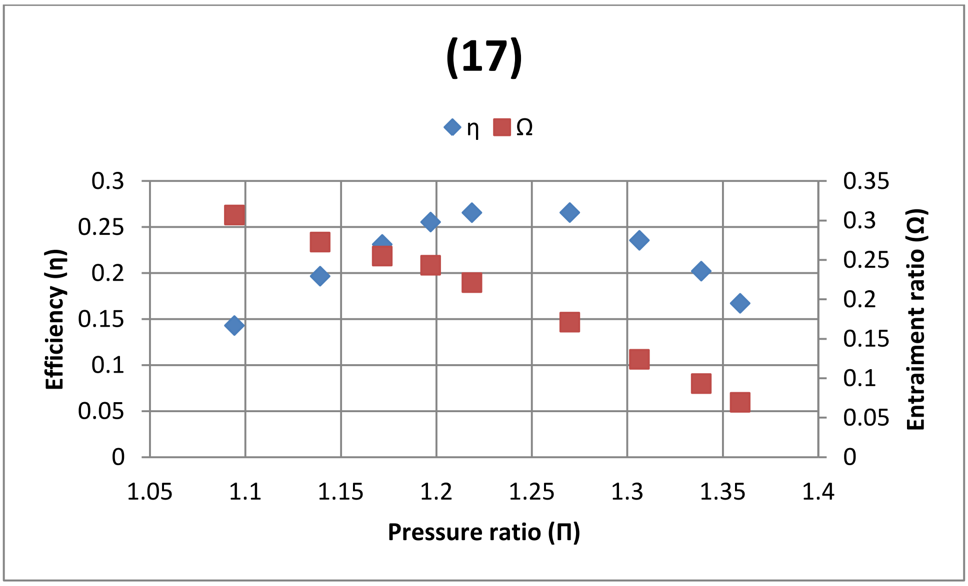
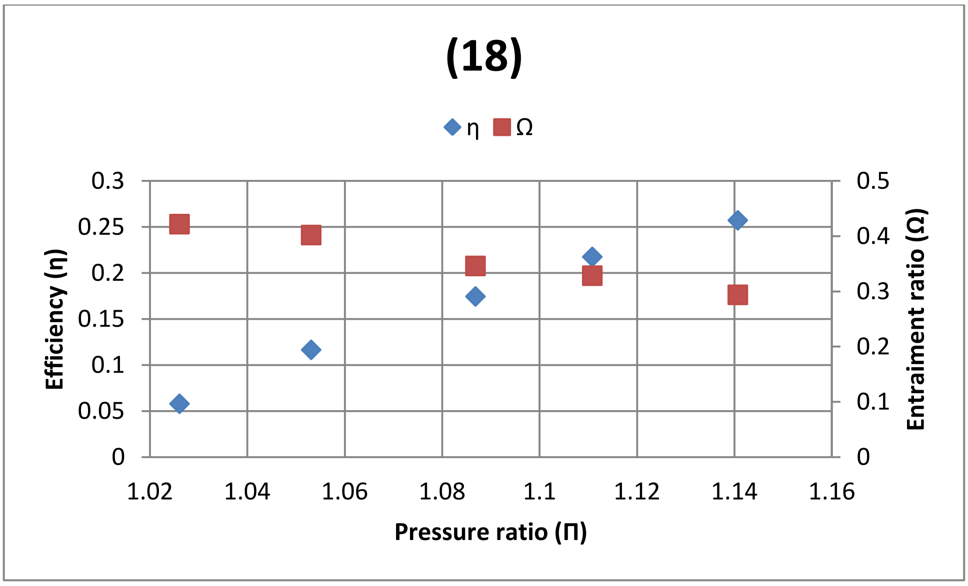
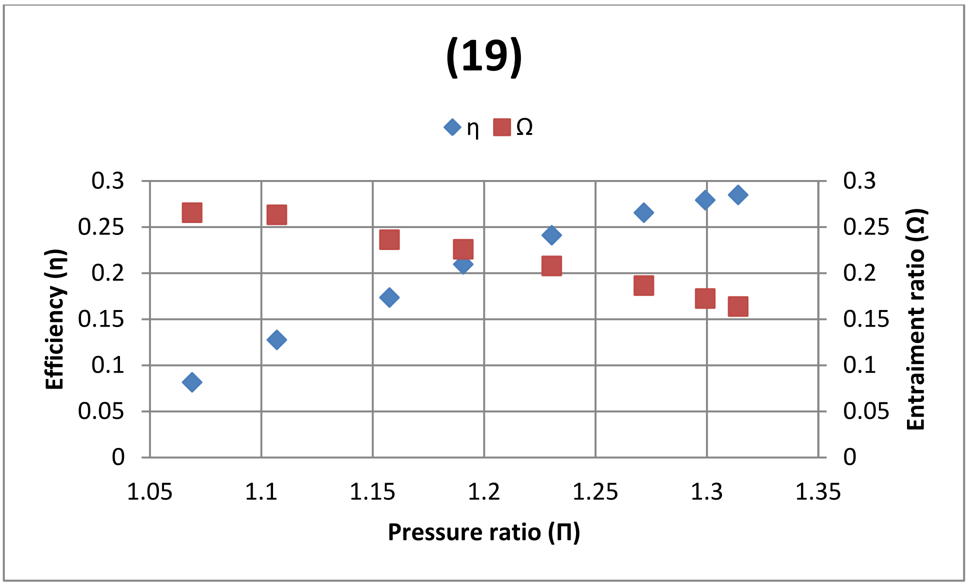
0.2
0.15
0.1
0.05
0
1.05 1.1 1.15 1.2 1.25 1.3 1.35
Pressure ratio (Π)

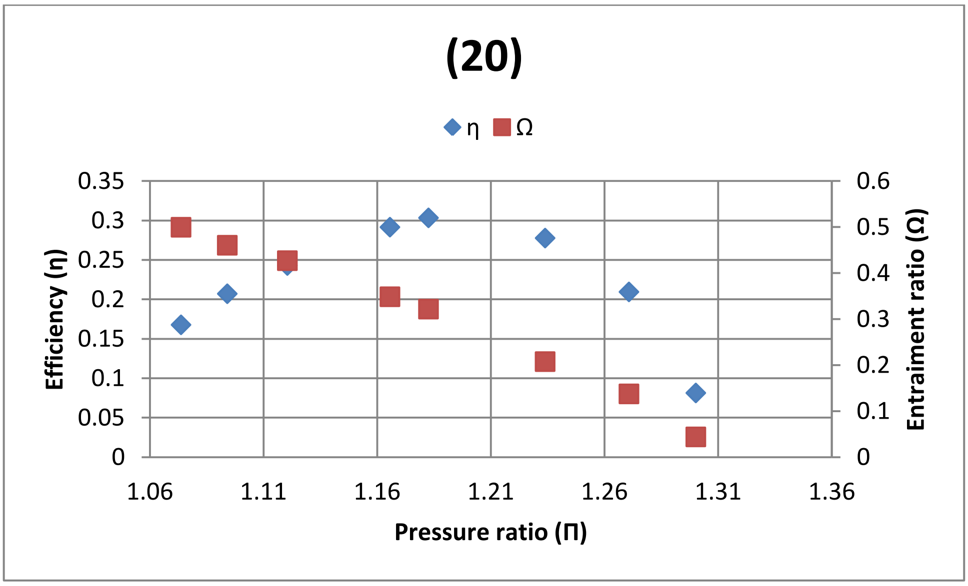

(15)
η Ω
Efficiency (η)
0.3
0.25
0.2
0.15
0.1
0.05
0
Entraiment ratio (Ω)
0.5
0.4
0.3
0.2
0.1
0
1.05 1.1 1.15 1.2 1.25 1.3
Pressure ratio (Π)

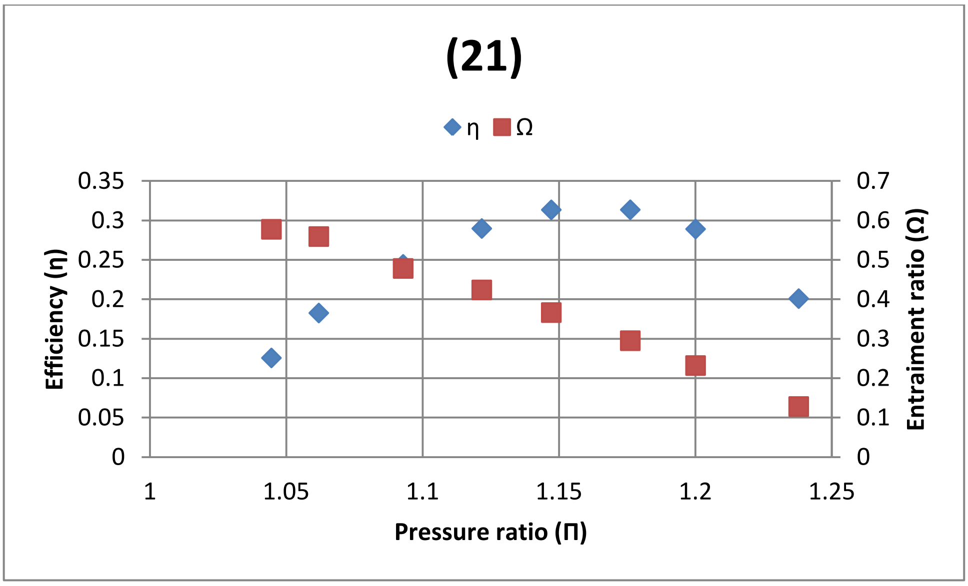

(16)
η Ω
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Efficiency (η)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Entraiment ratio (Ω)
1.1 1.12 1.14 1.16 1.18 1.2 1.22 1.24
Pressure ratio (Π)

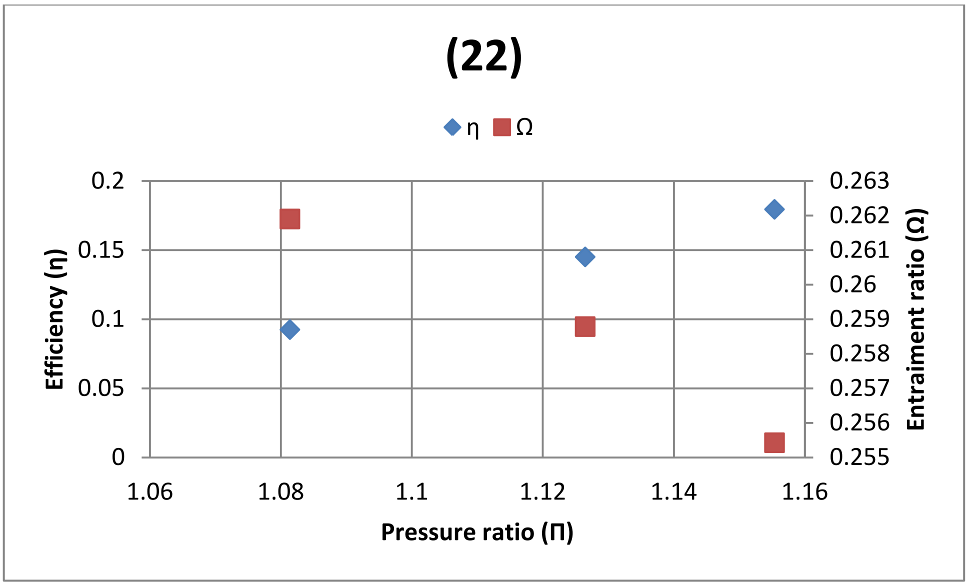

(17)
η Ω
0.3
0.25
0.2
0.15
0.1
0.05
0
Efficiency (η)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Entraiment ratio (Ω)
1.05 1.1 1.15 1.2 1.25 1.3 1.35 1.4
Pressure ratio (Π)

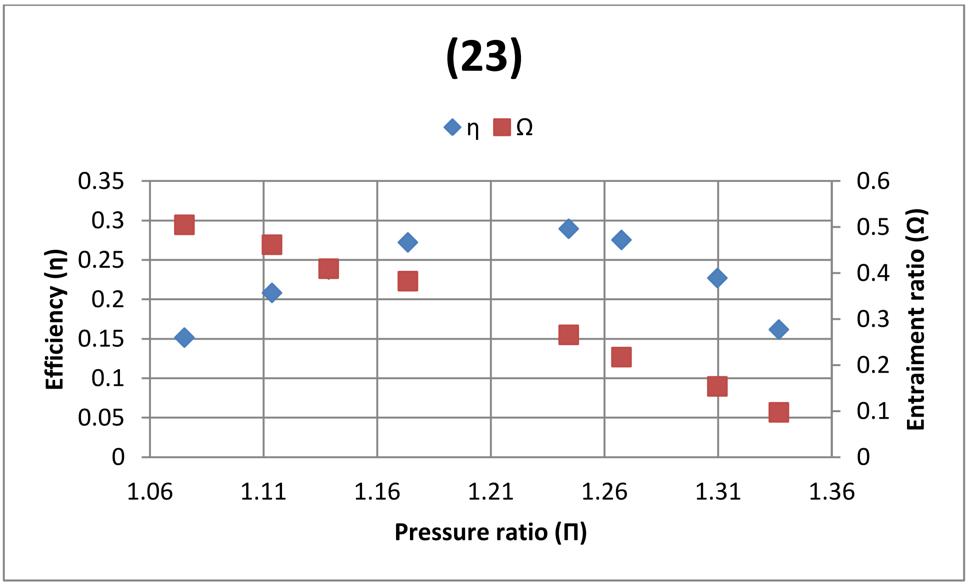

(18)
η Ω
0.3
0.25
0.2
0.15
0.1
0.05
0
Efficiency (η)
0.5
0.4
0.3
0.2
0.1
0
Entraiment ratio (Ω)
1.02 1.04 1.06 1.08 1.1 1.12 1.14 1.16
Pressure ratio (Π)

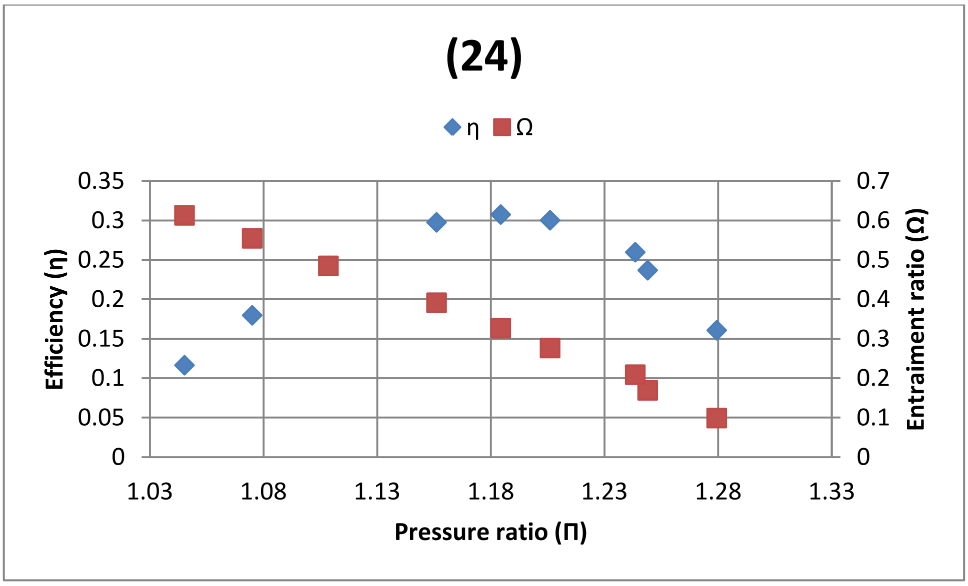

(19)
η Ω
Efficiency (η)
Entraiment ratio (Ω)
0
0.05
0.1
0.15
0.2
0.25
0.3
1.05
1.1
1.15
1.2
1.25
1.3
1.35
Pressure ratio (Π)


(20)
η Ω
Efficiency (η)
Entraiment ratio (Ω)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.5
0.6
1.06
1.11
1.16
1.21
1.26
1.31
1.36
Pressure ratio (Π)


(21)
η Ω
Efficiency (η)
Entraiment ratio (Ω)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.5
0.6
0.7
1
1.05
1.1
1.15
1.2
1.25
Pressure ratio (Π)


(22)
η Ω
Efficiency (η)
0.2
0.15
0.1
0.05
0
Entraiment ratio (Ω)
0.263
0.262
0.261
0.26
0.259
0.258
0.257
0.256
0.255
1.06
1.08
1.1
1.12
1.14
1.16
Pressure ratio (Π)


(23)
η Ω
Efficiency (η)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Entraiment ratio (Ω)
0.6
0.5
0.4
0.3
0.2
0.1
0
1.06
1.11
1.16
1.21
1.26
1.31
1.36
Pressure ratio (Π)


(24)
η Ω
Efficiency (η)
0.35
0.3
0.25
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0.1
0.05
0
Entraiment ratio (Ω)
0.7
0.6
0.5
0.4
0.3
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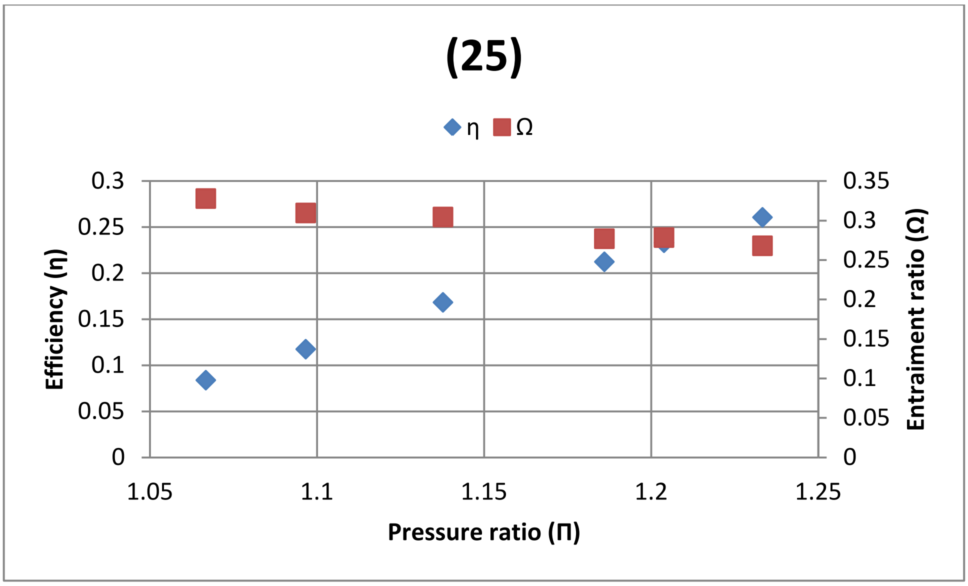
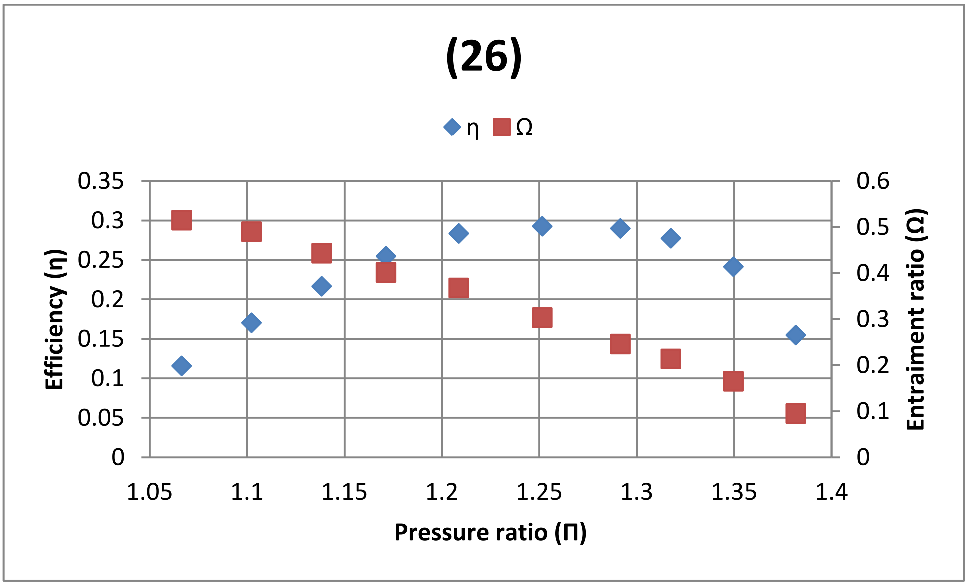
0
1.03
1.08
1.13
1.18
1.23
1.28
1.33
Pressure ratio (Π)


(25)
η Ω
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)
0.3
0.25
0.2
0.15
0.1
0.05
0
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1.05
1.1
1.15
1.2
1.25


(26)
η Ω
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)
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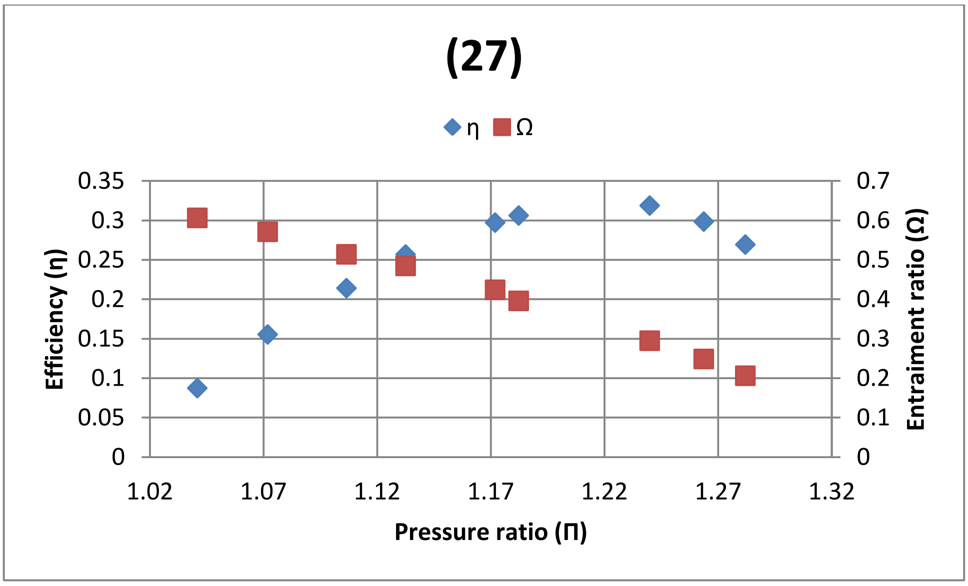
0.3
0.25
0.2
0.15
0.1
0.05
0
0.6
0.5
0.4
0.3
0.2
0.1
0
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4


(27)
η Ω
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)
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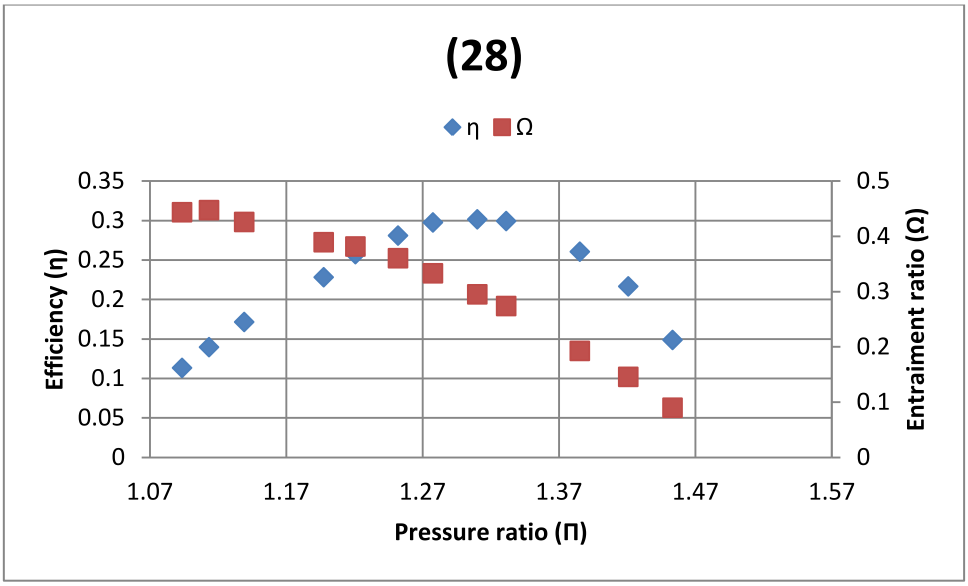
0.25
0.2
0.15
0.1
0.05
0
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.02
1.07
1.12
1.17
1.22
1.27
1.32


(28)
η Ω
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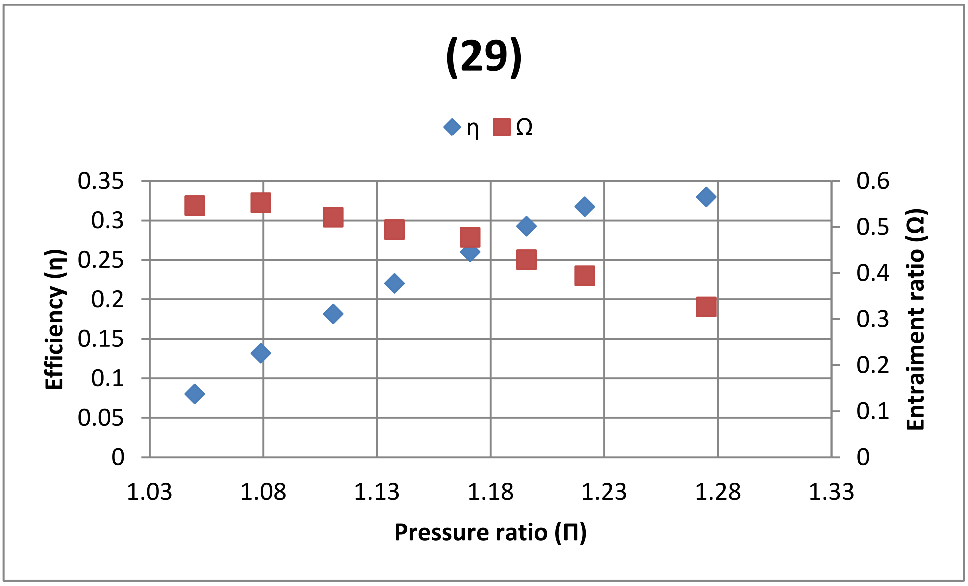
0.25
0.2
0.15
0.1
0.05
0
0.5
0.4
0.3
0.2
0.1
0
1.07
1.17
1.27
1.37
1.47
1.57
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)


(29)
η Ω
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0.3
0.25
0.2
0.15
0.1
0.05
0
0.6
0.5
0.4
0.3
0.2
0.1
0
1.03
1.08
1.13
1.18
1.23
1.28
1.33
Efficiency (η)
Entraiment ratio (Ω)
Pressure ratio (Π)

№1

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
2.598740	30.923270	-3.593439	28.235218	3.027855	0.564213	3.592067	0.186341	1.089999	2.553265	0.185658
2.714368	31.831807	-2.693887	28.295258	3.035029	0.451914	3.486943	0.148900	1.119761	3.404494	0.212694
3.272464	32.811018	-1.581961	28.107230	3.042415	0.303848	3.346263	0.099871	1.161387	4.559443	0.208403
4.536688	33.655300	-0.600576	27.761211	3.065126	0.170312	3.235438	0.055564	1.206495	5.760189	0.163134

№2

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
3.800516	32.913232	-1.487513	28.085400	3.564899	0.576941	4.141840	0.161839	1.166856	4.706461	0.258747
4.089216	33.801193	-0.495165	27.988519	3.520101	0.447981	3.968082	0.127264	1.202542	5.693077	0.255845
5.199277	34.912549	0.653494	27.915086	3.557678	0.356020	3.913698	0.100071	1.245675	6.885537	0.259274
2.494162	31.820395	-2.709067	28.205446	3.535224	0.697987	4.233211	0.197438	1.122661	3.476676	0.223437
2.478611	30.927837	-3.702637	28.123320	3.496475	0.777733	4.274208	0.222433	1.093933	2.655700	0.184223
4.248502	35.513913	1.202169	28.138235	3.517431	0.301452	3.818883	0.085702	1.256110	7.240985	0.238278

№3

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
1.504979	30.972660	-3.706612	28.202317	3.002393	0.548882	3.551275	0.182815	1.092100	2.612016	0.182495
3.495493	31.859742	-2.697793	27.992326	3.022100	0.395726	3.417826	0.130944	1.132023	3.715663	0.206296
4.044749	32.404251	-2.115246	28.016599	3.021985	0.329673	3.351658	0.109091	1.151026	4.251753	0.206648

№4

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
3.119324	30.944459	-3.643545	28.201440	3.508338	0.783569	4.291907	0.223345	1.090813	2.576206	0.170093
2.723987	31.841906	-2.693001	28.308715	3.483239	0.681351	4.164590	0.195608	1.118183	3.365441	0.199332
2.556907	32.842322	-1.634717	28.380266	3.452403	0.572858	4.025261	0.165930	1.148913	4.256751	0.220599
2.673298	33.767781	-0.545319	28.134951	3.470834	0.450304	3.921138	0.129739	1.191814	5.434693	0.229828
3.180567	34.828855	0.608698	28.066168	3.477542	0.332419	3.809962	0.095590	1.233240	6.587112	0.217865
4.467303	35.747842	1.550900	28.017943	3.469592	0.227511	3.697103	0.065573	1.267927	7.553905	0.178625

№5

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
2.801363	30.928568	-3.620140	27.888353	2.600354	0.504481	3.104836	0.194005	1.101160	2.841301	0.181741
3.161737	31.988991	-2.464845	28.124700	2.558256	0.414353	2.972609	0.161967	1.129516	3.668016	0.202319
3.560998	32.848343	-1.512200	28.140141	2.645109	0.301297	2.946406	0.113907	1.158696	4.498940	0.185988
5.530198	33.876498	-0.360106	27.988421	2.516059	0.135077	2.651136	0.053686	1.201986	5.692720	0.116639

№6

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
8.974352	36.891072	2.954432	32.383407	2.450372	0.156934	2.607306	0.064045	1.134427	4.371515	0.126573
7.805260	35.800100	1.712269	32.306147	2.527993	0.391895	2.919888	0.155022	1.103185	3.348521	0.205133
6.241674	34.853801	0.736782	32.410971	2.499057	0.645653	3.144710	0.258359	1.070548	2.296817	0.196517
5.284499	33.940372	-0.199057	32.279927	2.439041	0.862889	3.301930	0.353782	1.046913	1.520894	0.157096

№7

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
4.387005	30.960136	-3.642113	27.743404	3.295322	0.608878	3.904200	0.184770	1.109860	3.064592	0.152915
4.388532	31.892879	-2.581068	27.804293	3.349222	0.531292	3.880514	0.158631	1.141095	3.943511	0.174804
5.119014	32.885097	-1.465119	27.938819	3.275807	0.421170	3.696977	0.128570	1.170401	4.787801	0.180500
5.583904	33.869131	-0.406221	28.102504	3.349135	0.361699	3.710835	0.107998	1.198628	5.612551	0.182745
6.209364	34.842398	0.633411	28.016393	3.336252	0.255782	3.592035	0.076668	1.237500	6.686935	0.162184
6.711045	35.820617	1.657163	28.341993	3.318709	0.187106	3.505815	0.056379	1.255981	7.300584	0.135774

№8

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
1.980285	31.007688	-3.459737	28.475776	2.411075	0.753677	3.164752	0.312590	1.082336	2.358838	0.191364
1.343556	32.021771	-2.269597	28.399711	2.387887	0.612762	3.000649	0.256613	1.120163	3.435074	0.241217
3.021142	32.896438	-1.330470	28.410379	2.379121	0.502406	2.881527	0.211173	1.150263	4.297373	0.256197
5.424300	33.873365	-0.290662	28.364208	2.469758	0.358062	2.827819	0.144978	1.186359	5.320998	0.237003
6.185758	34.858964	0.770455	28.257584	2.408041	0.139819	2.547860	0.058063	1.226510	6.437706	0.123985

№9

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
4.982395	33.908316	-0.202623	31.879687	2.449879	0.816190	3.266068	0.333155	1.060943	1.947762	0.183747
5.195311	34.874032	0.781312	32.167340	2.391495	0.783775	3.175269	0.327734	1.080628	2.602042	0.229259
5.007057	35.792695	1.756959	32.095178	2.350853	0.593663	2.944515	0.252531	1.110986	3.575628	0.267839
5.345244	36.817932	2.844709	31.788687	2.433602	0.358205	2.791807	0.147191	1.154908	4.938407	0.237649

6.830606	37.801986	3.828710	31.886395	2.373634	0.203738	2.577372	0.085834	1.181458	5.805939	0.168892

№10

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
5.211152	33.762719	-0.066574	31.896121	2.927997	0.953334	3.881331	0.325593	1.055160	1.764983	0.136543
4.889587	34.719854	0.771841	32.153114	2.849984	0.876211	3.726195	0.307444	1.075929	2.450217	0.183920
5.745072	35.800521	1.892050	32.390665	2.893897	0.749660	3.643557	0.259049	1.100930	3.282079	0.221185
5.936772	36.753540	2.839024	32.088357	2.922454	0.594187	3.516641	0.203318	1.141064	4.543657	0.253650
6.873954	37.839507	3.931956	32.169277	2.934518	0.489661	3.424179	0.166863	1.171482	5.538968	0.261127
7.985999	38.694548	4.783655	31.658711	2.964084	0.277668	3.241752	0.093678	1.218077	6.927623	0.203274
10.096487	39.749518	5.807067	31.885640	2.869013	0.139136	3.008149	0.048496	1.242281	7.752309	0.122696

№11

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
1.387557	30.927069	-3.543708	28.558487	2.938216	0.846188	3.784405	0.287994	1.075735	2.177353	0.145580
0.842250	31.841990	-2.483921	28.480364	2.989741	0.724607	3.714348	0.242365	1.110366	3.164959	0.189085
1.607795	32.833789	-1.400147	28.374374	2.925564	0.622610	3.548174	0.212817	1.149597	4.272668	0.235990
2.403329	33.853296	-0.283618	28.418349	2.969190	0.528816	3.498006	0.178101	1.183749	5.254911	0.254635
3.315202	34.919881	0.794611	28.370579	3.081700	0.404290	3.485990	0.131191	1.223203	6.371988	0.239694
4.402750	35.800378	1.735627	28.316999	2.895431	0.274960	3.170391	0.094963	1.256754	7.313992	0.204379

№12

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
3.268904	30.942455	-3.563260	28.340284	3.264514	0.882183	4.146697	0.270234	1.084009	2.397984	0.120964

3.010840	31.883512	-2.547286	28.526138	3.218368	0.862169	4.080537	0.267890	1.109206	3.139069	0.161394
3.038252	32.918414	-1.308438	28.632736	3.152280	0.810079	3.962358	0.256982	1.140394	4.052593	0.204547
2.944329	33.855046	-0.279084	27.934628	3.142925	0.672845	3.815770	0.214083	1.203632	5.727637	0.253011
3.307302	34.845565	0.761048	27.881056	3.199681	0.597852	3.797533	0.186847	1.241555	6.779507	0.271995
4.005370	35.795262	1.771788	27.918319	3.160574	0.511047	3.671621	0.161694	1.273757	7.693156	0.275938
4.724036	36.766242	2.767774	27.737052	3.160177	0.377558	3.537735	0.119474	1.317645	8.863253	0.243800
5.734742	37.729326	3.767943	27.851149	3.125499	0.263249	3.388749	0.084226	1.346416	9.707278	0.196444
6.836535	38.366456	4.370938	27.830008	3.246066	0.214328	3.460393	0.066027	1.370784	10.377770	0.172123

№13

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
5.998720	35.774284	1.767172	31.798423	3.356303	0.826092	4.182395	0.246132	1.122184	3.895133	0.207143
5.918619	34.641461	0.545610	32.004141	3.319217	0.990738	4.309954	0.298485	1.079261	2.544085	0.153794
5.654125	34.080701	0.047389	32.243945	3.333039	1.090962	4.424001	0.327318	1.053974	1.745271	0.109523
5.061897	33.198195	-0.901498	32.095785	3.260543	1.143229	4.403772	0.350625	1.030512	0.982937	0.062994

№14

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
2.300610	30.912755	-3.541686	28.270354	3.958909	0.792508	4.751418	0.200183	1.087433	2.485473	0.088288
2.577215	31.864758	-2.368433	28.101664	3.961195	0.752903	4.714098	0.190070	1.127116	3.593716	0.124850
2.719094	32.826573	-1.369392	28.074995	3.949287	0.703503	4.652790	0.178134	1.162407	4.586396	0.154606
3.331065	33.793266	-0.243401	27.841974	3.984205	0.636932	4.621138	0.159864	1.206669	5.787844	0.180773
3.769838	34.825438	0.766735	27.851845	3.966875	0.575026	4.541901	0.144957	1.243174	6.812120	0.201095
4.612399	35.570867	1.668003	27.793218	3.995319	0.518137	4.513457	0.129686	1.273228	7.633323	0.210138
4.979908	36.725156	2.825109	27.945827	4.008242	0.447765	4.456007	0.111711	1.307417	8.635293	0.210069

№15

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
2.791217	30.392149	-4.063274	28.342201	2.182325	0.910684	3.093010	0.417300	1.066418	1.892867	0.144873
1.328896	31.298315	-2.983540	28.108775	2.093200	0.799786	2.892986	0.382088	1.107150	3.029058	0.215143
1.289276	32.244659	-1.930791	28.271527	2.085890	0.725904	2.811794	0.348007	1.134530	3.823507	0.249297
1.776436	33.176726	-0.943136	28.235626	2.071384	0.607978	2.679362	0.293513	1.168121	4.774933	0.275070
3.297360	34.122027	0.093750	28.132789	2.029790	0.478815	2.508605	0.235894	1.205378	5.813862	0.278989
3.916331	35.108330	1.073562	28.134813	2.142443	0.306922	2.449365	0.143258	1.239746	6.789366	0.223572
5.187019	36.240307	2.313219	28.201457	2.114919	0.179344	2.294262	0.084799	1.276363	7.846884	0.154175

№16

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
5.226652	39.365823	5.458063	32.081802	2.190158	0.197671	2.387829	0.090254	1.219867	7.095245	0.163532
6.613913	37.793391	4.001350	32.179064	1.970141	0.512957	2.483098	0.260366	1.166989	5.408003	0.288300
5.948757	36.854130	3.000870	32.077897	2.022662	0.622512	2.645174	0.307769	1.142091	4.585147	0.295214
5.805605	35.809566	1.942142	32.006454	2.127644	0.716936	2.844580	0.336962	1.112308	3.615646	0.261803
5.500968	35.042686	1.155589	31.933109	2.176188	0.826016	3.002204	0.379570	1.091185	2.928349	0.228012
5.488441	34.048458	0.103961	32.054422	2.050951	1.059756	3.110707	0.516714	1.056252	1.813297	0.172240
5.111025	32.156179	-2.046814	31.569619	2.133088	1.274611	3.407699	0.597543	1.016479	0.521317	0.053292

№17

Tsuction	Poutlet	Toutlet	P0(comp	MF_motiv	MF_suction	MF_outlet	entraiment	Pressure	pressure lift	efficiency

			suction)	e			rat	rat		
4.058888	30.905907	-3.576295	28.066031	2.961813	0.909639	3.871452	0.307122	1.094319	2.663777	0.143106
3.542891	31.961178	-2.389839	27.884319	3.004381	0.819639	3.824020	0.272814	1.139204	3.905475	0.196741
3.694377	32.910316	-1.337462	27.914531	2.976379	0.759198	3.735577	0.255074	1.171727	4.823309	0.231312
3.734681	33.906092	-0.210541	28.144078	2.863205	0.696976	3.560182	0.243425	1.197063	5.581693	0.255593
3.950065	34.809570	0.651024	28.351838	2.834451	0.627548	3.462000	0.221400	1.218682	6.246289	0.265803
3.928218	35.735048	1.625446	27.955261	2.931454	0.502172	3.433626	0.171305	1.269932	7.595699	0.265900
4.502672	36.719502	2.744741	27.916963	2.936885	0.364653	3.301538	0.124163	1.306388	8.611847	0.235721
5.324270	37.669522	3.719763	27.950959	3.005064	0.280560	3.285624	0.093362	1.338791	9.532554	0.202222
6.894072	38.439608	4.505733	28.087639	3.046959	0.212096	3.259054	0.069609	1.359154	10.157598	0.167267

№18

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
5.077549	36.439946	2.474119	31.827845	2.981567	0.875835	3.857401	0.293750	1.140728	4.495482	0.257225
4.926107	35.472307	1.447202	31.828069	2.949703	0.968836	3.918539	0.328452	1.110854	3.539830	0.217554
4.777184	34.799603	0.828929	31.898400	3.059704	1.058928	4.118632	0.346088	1.086862	2.781184	0.174491
3.969597	33.887708	-0.181647	32.058444	2.902907	1.167183	4.070090	0.402074	1.053136	1.709820	0.116466
4.720606	32.985561	-1.163952	32.029750	2.885107	1.216938	4.102045	0.421800	1.026105	0.839192	0.057845

№19

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motive	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
0.566747	31.019293	-3.453533	28.803298	3.504896	0.931080	4.435976	0.265651	1.069000	2.002187	0.081451
2.089658	31.909442	-2.445216	28.597062	3.459155	0.910953	4.370108	0.263346	1.107031	3.085109	0.127518
2.130335	32.794745	-1.466574	28.157793	3.552032	0.839536	4.391569	0.236354	1.157589	4.464523	0.173514
2.615172	33.795169	-0.341590	28.197164	3.527725	0.796979	4.324704	0.225919	1.190712	5.412856	0.209605
2.840231	34.785561	0.677531	28.081737	3.535458	0.734755	4.270213	0.207824	1.230424	6.514364	0.241152

3.185293	35.808125	1.776371	27.969670	3.556820	0.663352	4.220172	0.186501	1.271773	7.652057	0.265649
3.305501	36.585708	2.642193	27.982174	3.578766	0.617150	4.195915	0.172448	1.299317	8.428067	0.279298
3.508776	37.192796	3.181604	28.106671	3.609442	0.591115	4.200557	0.163769	1.314084	8.889593	0.284954

№20

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motiv e	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
3.923717	30.250540	-4.224228	28.114129	2.026669	1.012997	3.039666	0.499834	1.073746	2.077639	0.167868
3.813387	31.202566	-3.208086	28.410876	2.041487	0.940593	2.982080	0.460739	1.094100	2.683640	0.207284
3.532747	32.024044	-2.247350	28.464011	2.069799	0.884205	2.954004	0.427194	1.120529	3.444658	0.243092
3.158888	33.165463	-0.958198	28.345147	2.091432	0.729510	2.820942	0.348809	1.165658	4.713335	0.291703
3.450312	33.650970	-0.404437	28.326864	2.050898	0.660273	2.711171	0.321943	1.182621	5.196394	0.303518
4.289990	34.979584	0.960803	28.222606	2.088927	0.434021	2.522948	0.207772	1.233918	6.631206	0.277871
5.270850	36.211398	2.273815	28.351238	2.016745	0.277612	2.294357	0.137653	1.270806	7.716572	0.209617
7.152937	36.979913	3.087218	28.296512	2.081200	0.091844	2.173044	0.044130	1.300226	8.538781	0.081482

№21

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motiv e	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
8.445151	39.823797	5.847185	32.046421	2.107268	0.269774	2.377043	0.128021	1.237907	7.653520	0.200826
6.337792	38.833740	4.877862	32.212226	2.081694	0.482720	2.564413	0.231888	1.200096	6.474892	0.289028
5.495234	37.871842	3.963018	32.055329	2.058756	0.607179	2.665935	0.294925	1.176164	5.672391	0.313493
5.071025	36.830576	2.925160	31.971063	2.041937	0.747831	2.789768	0.366236	1.147208	4.726036	0.313421
4.903088	35.854101	1.923721	31.835595	2.038168	0.863530	2.901698	0.423680	1.121723	3.890690	0.289718
4.827889	34.969120	1.016442	31.864123	2.072039	0.990713	3.062752	0.478134	1.092885	2.972042	0.244267
4.895919	33.922710	0.068823	31.827164	2.013275	1.125459	3.138735	0.559019	1.061971	1.979553	0.182573
5.320623	33.746410	-0.185227	32.165844	2.181663	1.259650	3.441313	0.577381	1.044596	1.440696	0.125613

№22

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motiv e	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
4.131381	30.895353	-3.522700	28.394297	3.454596	0.904765	4.359361	0.261902	1.081401	2.325596	0.092431
3.399950	31.954399	-2.291905	28.170458	3.408270	0.882010	4.290280	0.258785	1.126485	3.587940	0.145080
3.710475	32.877298	-1.147421	28.258170	3.374923	0.862032	4.236956	0.255423	1.155400	4.421964	0.179521

№23

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motiv e	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
3.582119	30.637489	-3.711874	28.326243	2.147996	1.085118	3.233115	0.505177	1.075234	2.143713	0.151664
1.695893	31.575935	-2.637327	28.148626	2.127097	0.982564	3.109660	0.461927	1.113764	3.225295	0.208373
3.907640	32.248505	-1.835498	28.160909	2.158266	0.884455	3.042721	0.409799	1.138698	3.927994	0.237991
4.062621	33.356458	-0.592163	28.269446	2.120255	0.811501	2.931757	0.382738	1.173539	4.932630	0.272388
3.961317	35.221688	1.388538	28.127017	2.179732	0.579811	2.759543	0.266001	1.244314	6.915582	0.289702
4.547300	36.361485	2.574185	28.478539	2.206017	0.480131	2.686148	0.217646	1.267526	7.674518	0.275545
5.382542	37.189285	3.442633	28.186567	2.170235	0.334127	2.504362	0.153959	1.309711	8.794263	0.227202
6.264731	38.184786	4.385938	28.342188	2.180066	0.212744	2.392811	0.097586	1.336763	9.619668	0.161895

№24

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motiv e	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
8.552990	41.068102	7.148431	31.914878	2.212508	0.218578	2.431086	0.098792	1.279412	8.968895	0.160656

8.858758	40.385303	6.478262	32.149470	2.179040	0.368453	2.547492	0.169089	1.249045	8.052367	0.236758
7.085910	39.735113	5.818502	31.817065	2.106593	0.439638	2.546231	0.208696	1.243587	7.783097	0.259657
6.604259	38.770994	4.833513	32.011278	2.146019	0.593195	2.739214	0.276416	1.206106	6.625410	0.300180
6.776293	37.525118	3.909665	31.555694	2.201980	0.719477	2.921457	0.326741	1.184395	5.842167	0.307386
6.146551	36.931091	3.121610	31.821696	2.127155	0.832016	2.959170	0.391140	1.156154	4.988034	0.297519
5.827020	35.375398	1.565188	31.803799	2.128878	1.031696	3.160574	0.484620	1.108578	3.464778	0.242266
5.629792	34.335937	0.461487	31.832830	2.159733	1.197777	3.357510	0.554595	1.075054	2.397143	0.179654
5.427357	33.161584	-0.841869	31.637890	2.139377	1.311019	3.450396	0.612804	1.045271	1.436228	0.116397

№25

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motiv e	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
0.499474	30.349081	-4.169666	28.321721	3.018717	0.989677	4.008393	0.327847	1.066763	1.899381	0.083760
0.833463	31.224422	-3.169276	28.342355	3.111398	0.963174	4.074573	0.309563	1.096655	2.752009	0.117412
1.089228	32.238142	-2.042882	28.208134	3.014052	0.917642	3.931694	0.304455	1.137733	3.902732	0.168285
1.578533	33.324786	-0.842054	27.969531	3.009983	0.833577	3.843560	0.276937	1.186033	5.227103	0.212326
2.073064	33.884544	-0.128576	28.019391	2.927258	0.814944	3.742203	0.278399	1.203871	5.738218	0.233021
3.182929	35.129646	1.130332	28.342614	2.855042	0.765176	3.620219	0.268009	1.233337	6.646230	0.260611

№26

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motiv e	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
1.959566	30.194888	-4.226623	28.214614	2.252672	1.160418	3.413090	0.515130	1.066474	1.882072	0.115904
1.728544	31.308948	-2.988989	28.310802	2.253320	1.104475	3.357795	0.490155	1.102332	2.906473	0.170500
1.218650	32.401099	-1.718963	28.344679	2.289549	1.015098	3.304647	0.443361	1.138359	3.938116	0.216736
1.081518	33.295715	-0.779087	28.300315	2.277534	0.914684	3.192218	0.401612	1.171361	4.870908	0.254880
1.585870	34.348247	0.475301	28.306304	2.255564	0.829879	3.085443	0.367925	1.208708	5.930920	0.283657
2.609737	35.208430	1.390227	27.998337	2.304784	0.699633	3.004416	0.303557	1.251570	7.077015	0.292786

2.444075	36.139767	2.338427	27.858968	2.276158	0.560342	2.836500	0.246179	1.291658	8.160414	0.290025
3.487057	37.154831	3.444223	28.068185	2.289777	0.489571	2.779349	0.213807	1.317568	8.955272	0.277584
3.628254	38.243536	4.446506	28.173721	2.297033	0.379656	2.676690	0.165281	1.349676	9.908183	0.241550
4.901067	38.992269	5.109464	28.073240	2.212566	0.210906	2.423472	0.095322	1.381718	10.772135	0.154961

№27

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motiv e	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
6.597256	41.159930	7.290326	32.010202	2.276468	0.469086	2.745554	0.206059	1.282002	9.053954	0.269387
6.154221	40.191342	6.446584	31.711153	2.277688	0.566238	2.843926	0.248602	1.263725	8.387487	0.298516
5.421111	39.648486	5.860740	31.871353	2.292242	0.676044	2.968286	0.294927	1.239930	7.672108	0.318799
4.888339	37.753574	3.943750	31.845938	2.293272	0.908042	3.201314	0.395959	1.182294	5.821099	0.306207
4.810592	37.563023	3.782097	31.991036	2.269905	0.962450	3.232355	0.424005	1.171933	5.510839	0.297206
4.741309	36.122463	2.354717	31.825126	2.236476	1.083970	3.320446	0.484678	1.132547	4.227581	0.256819
4.625711	35.321217	1.380760	31.841538	2.298311	1.181457	3.479768	0.514054	1.106533	3.400585	0.214090
4.577046	34.096456	0.221557	31.748093	2.264547	1.293378	3.557925	0.571142	1.071867	2.286123	0.155395
4.798455	32.957693	-0.911920	31.612700	2.275074	1.379674	3.654748	0.606430	1.040909	1.295274	0.087323

№28

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motiv e	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
2.759015	30.903049	-3.562310	28.130637	2.506923	1.112047	3.618970	0.443591	1.093651	2.646284	0.113319
2.528528	31.521035	-2.768826	28.174195	2.490252	1.114135	3.604387	0.447398	1.113420	3.210940	0.139596
2.444849	32.555334	-1.653706	28.415908	2.546472	1.084659	3.631131	0.425946	1.139236	3.978876	0.171460
2.227769	33.461708	-0.566514	27.802308	2.506813	0.975941	3.482753	0.389315	1.197509	5.518952	0.228155
3.146177	34.333638	0.392423	28.032352	2.462847	0.939677	3.402524	0.381541	1.220767	6.208986	0.257392
3.084896	35.502156	1.617637	28.262966	2.482425	0.894530	3.376956	0.360345	1.252008	7.145985	0.280942
2.949114	36.260871	2.344555	28.262491	2.454669	0.817569	3.272238	0.333067	1.277603	7.878926	0.297549

2.845230	37.383341	3.495562	28.377259	2.507902	0.739846	3.247748	0.295006	1.310138	8.849454	0.301499
3.052926	37.956166	4.114168	28.356969	2.480543	0.679197	3.159741	0.273810	1.331319	9.445976	0.299332
3.779903	39.318067	5.436801	28.237310	2.483562	0.478291	2.961854	0.192583	1.385324	10.936202	0.260518
4.503783	40.372775	6.412332	28.279013	2.444384	0.355933	2.800318	0.145613	1.420827	11.957796	0.216580
6.099626	41.509385	7.519768	28.394288	2.467421	0.221489	2.688910	0.089765	1.453294	12.947109	0.148689

№29

Tsuction	Poutlet	Toutlet	P0(comp suction)	MF_motiv e	MF_suction	MF_outlet	entraiment rat	Pressure rat	pressure lift	efficiency
5.366117	40.844926	6.913778	31.932795	2.449413	0.800444	3.249856	0.326790	1.274933	8.808010	0.329939
4.858433	39.237426	5.372013	32.027471	2.492133	0.982925	3.475057	0.394411	1.221474	7.114423	0.317565
4.454327	38.194760	4.346486	31.873823	2.488916	1.068703	3.557619	0.429385	1.195843	6.255160	0.292843
4.520703	37.541735	3.813862	31.992044	2.472061	1.181366	3.653427	0.477887	1.171059	5.483802	0.260263
4.331793	36.197500	2.377474	31.748675	2.490316	1.231872	3.722187	0.494665	1.137767	4.382990	0.220380
4.407765	35.408857	1.561967	31.811642	2.489269	1.298123	3.787392	0.521488	1.110811	3.532274	0.181682
4.500504	34.300217	0.420979	31.736857	2.456439	1.358651	3.815090	0.553098	1.078960	2.510147	0.131927
4.562342	33.078474	-0.887288	31.454063	2.488256	1.360471	3.848727	0.546757	1.049888	1.571814	0.080338