Parallel Work of CO_2 Ejectors Installed in a Multi-Ejector Module of Refrigeration System

2016 J. Phys.: Conf. Ser. 745 032160

(http://iopscience.iop.org/1742-6596/745/3/032160)

PARALLEL WORK OF CO2 EJECTORS INSTALLED IN A MULTI-EJECTOR MODULE OF REFRIGERATION SYSTEM

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Abstract. A performance analysis on of fixed ejectors installed in a multi-ejector module in a CO2 refrigeration system is presented in this study. The serial and the parallel work of four fixed-geometry units that compose the multi-ejector pack was carried out. The executed numerical simulations were performed with the use of validated Homogeneous Equilibrium Model (HEM). The computational tool ejectorPL for typical transcritical parameters at the motive nozzle were used in all the tests. A wide range of the operating conditions for supermarket applications in three different European climate zones were taken into consideration. The obtained results present the high and stable performance of all the ejectors in the multi-ejector pack.

1. Introduction

Economical and ecological benefits obtained in the case of a CO_2 refrigeration system with implemented ejector are well known. The chemical characteristic of carbon-dioxide ensures safety of work for the environment as well as the refrigeration unit staff. A numerous investigations were collected into comprehensive review by Elbel and Lawrence (2016). The described study provides a wide scope of COP increments according to the work recovery as a result of ejector implementation. Nevertheless, further improvement of the ejector performance is still possible including geometry modifications. Investigations which concerned various system layouts brings also perspective results of COP improvement.

Research focused on the two proposed system layouts with ejectors described by Yari and Mahmoudi (2011), found that the possible COP improvements ranged from 17.2% to 31.5%. A comparison have been done according to the conventional cascade refrigeration cycle. A wide range of energetic and exergetic analyses concerning the enhancement of the two-evaporator refrigeration cycle with a two-stage ejector were presented by Bai et al. (2015). Theses authors proved a positive influence in a form of dual cooling temperatures, higher COP as well as less amount of the destructed exergy. Other refrigeration unit studies were focused on the ejector efficiency in the light if variable conditions of the heat rejection. Studies provided by Dresher et al. (2007), Elbel (2011), Nakagawa et al. (2011), Banasiak et al. (2012) and Lucas and Koehler (2012) reported up to a 60% COP increments in

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laboratory tests based on the single-ejector system. In the case of commercial systems with a single ejector, this value reached nearly 20% and was described by Girotto (2000).

One of the most crucial exploitation problems of CO_2 ejector system is a device regulation. A solution called *Multijet* described by Hafner et al. (2014) is designed for refrigeration units in supermarkets and it is based on the parallel working fixed-geometry ejectors. Such a multi-ejector module contains four vapour ejectors in order to cover the whole range of the system cooling load. This number of the ejectors allows the binary regulation of the module load. Total amount of the considered configuration is equal to fifteen. The idea of such a regulation is schematically illustrated in Figure 1. In this study, configurations marked in blue were investigated, i.e. a combinations of the three smallest units.

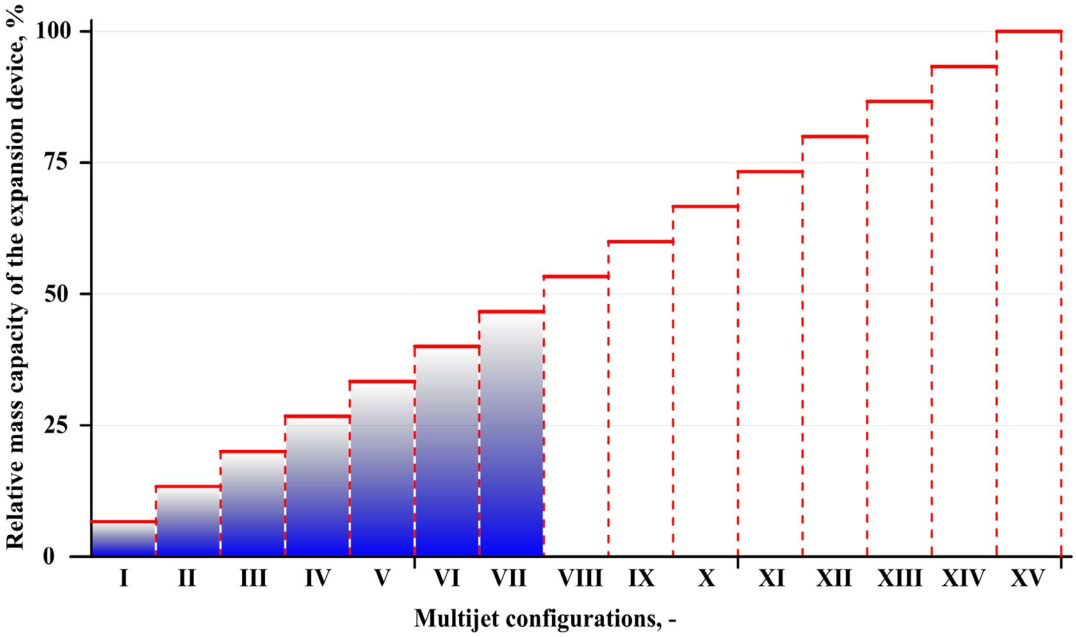

Figure 1: Idea of the refrigeration system control using the fixed ejectors in the multi-ejector module.

Having on regard further development of previous studies provided by Smolka et al. (2016), performance analysis of available configurations were realised. Namely, a fully developed 3-D domain of the module, including ducts and collectors, were generated. The computations were executed on the basis of the operating conditions characteristic for the supermarkets refrigeration unit. The validation data from the laboratory tests were provided by SINTEF Energy and confronted with the results of the numerical simulation. In the results section, the global performance of the whole module as well as particular ejectors was presented. The influence of module ducts were analysed as well. Overall conclusions on obtained results show promising perspective of the exploitation stability and regulation possibilities in case of each configuration.

2. Multi-ejector module

The developed multi-ejector module contains four vapour ejectors and two liquid ejectors. The parallel work of particular ejectors is ensured by the collectors and ducts connected to the motive nozzle, suction nozzle and outlet of the ejectors. Three ejectors which were taken into consideration in this paper were called EJ1, EJ2 and EJ3. An experimental investigation of the multi-ejectormodule were provided by Banasiak et al. (2015). These authors showed experimental results based on the pilot industrial installations located in three different European sub-climates, namely Mediterranean, Central European and North European. The installations (refrigeration units) are supplying supermarkets requisition of heating and cooling processes. For proper regulation in various operating conditions, measurement equipment were installed as well. Crucial parameters of multi-ejector module work are pressure in collectors. However, due to collateral purposes of the installation, additional parameters must be known as well. From the point of view of presented paper, the most crucial are measurement of mass streams flowing into motive and suction collector as well as pressure and temperature in this collectors. These two were used for the validation purposes.

3. Computational procedure

3.1. Computational domain

According to the configurations marked in blue in Figure 1 and listed in Table 1, the authors took into consideration seven configurations which correspond to the smallest cooling capacities. Each configuration can be obtained by simply turning on or off the proper valves. Such a situation was set up into the simulations. However, the back-pressure valves in the collector ducts from the evaporator were concerned as constantly opened or closed. So these valves were simulated in this same manner as motive and outlet collector duct. Moreover, the interference of measurement probes was neglected. Hence, seven various geometries which contain representation of ejectors and module ducts were used in the analysis.

3.2. Numerical grid

Within the mentioned geometry, a fully structured grid of the multi-ejector module was generated and implemented to the commercial solver Ansys FLUENT. A numerical mesh of high quality elements was necessary for providing stability of iterative computations. All of the mesh generation processes were executed using a commercial mesh generator Ansys ICEM-CFD. The details of the generated numerical grid are presented in Figure 2. A distribution of the elements as well as the mesh size were adjusted taking into consideration proper values of the aspect ratio (the average value was 2.65) and the overall quality (the average value was 0.92). Such a procedure was used to prepare the mesh of all three ejector that compose the considered part of the multi-ejector module. Moreover, the domain included one half of the module only due to device symmetry.

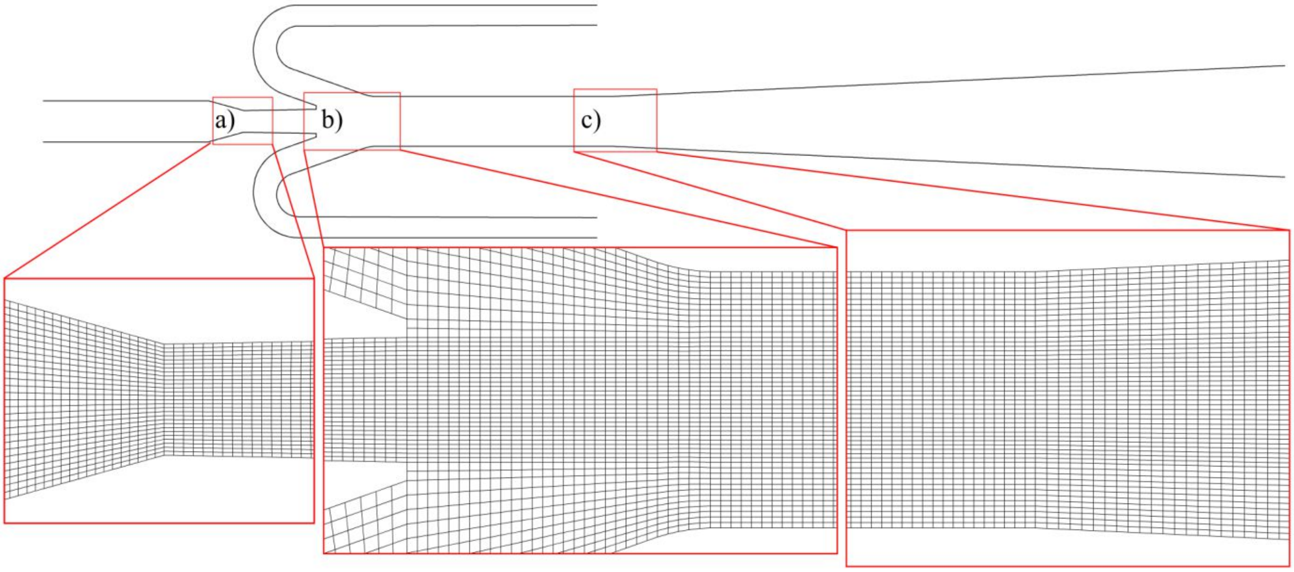

Figure 2: Details of a fully structural grid used in the vicinity of (a) the motive nozzle throat, (b) pre-mixing chamber and (c) the beginning of the diffuser.

3.3. Mathematical model

Investigations of Collarossi et. al (2012), Smolka et. al (2013), and Lucas et. al (2014) presented numerical models of CO_2 two-phase flow through an ejector which were based on the Homogeneous Equilibrium Model (HEM) and Homogeneous Relaxation Model (HRM) implementations. In this paper, the HEM approach was used for all the simulations. This formulation was extensively tested and eventually validated using a number of ejector geometries and operating conditions for carbon-dioxide flow by Palacz et. al (2015). The main assumption of the HEM formulation is that the local flow parameter quantities, such as velocity, pressure and temperature, are the same in both the liquid and gaseous phases. Hence, over the entire application range the fluid properties are only dependent on the enthalpy and pressure. The Realizable K-ε model was used during the turbulence modelling, as in a similar manner was presented by Smolka et. al (2013), Palacz et. al (2015).

The model was implemented on a computational platform called *ejectorPL* described and extensively tested by Palacz et al. (2015). The scheme of *ejectorPL* that was used for series of computations is illustrated in Figure 3. For the purpose of the multi-ejector module, the mesh generation process was partially manually performed and implemented to the mentioned tool using a commercial software Ansys ICEM-CFD. In this half-automatised process, the parameters of the unit ejector meshes in every configuration were constant. In this manner, a comparison between the considered cases were independent on the mesh generated in every configuration.

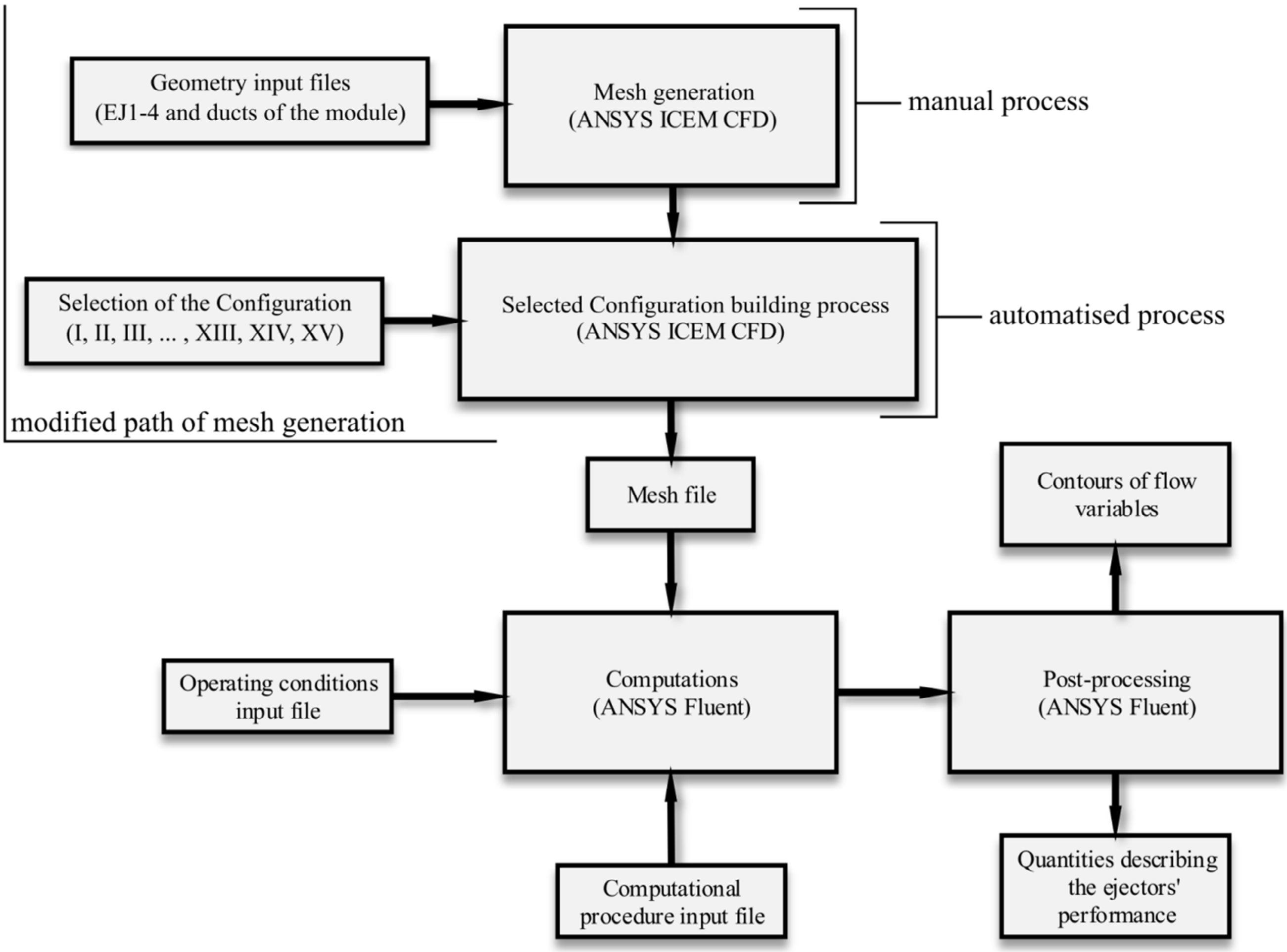

Figure 3: Scheme of the *ejectorPL* software adapted to 3-D simulations of the multi-ejector module.

The computations were performed using commercial solver Ansys Fluent (see Figure 3). Due to the software used, the results of every configuration were obtained after the same number of iterations. Every iteration process takes less than 10 hours of the computational time at high-performance computing cluster installed at the Institute of Thermal Technology, Gliwice, Poland. Levels of the residuals after last iteration were below a value of 10^{-5} for all the governing equations.

3.4. *Operating conditions for the considered configurations*

The experimental research of Haida et. al (2016) delivered data of the typical operating conditions for the supermarket refrigeration unit for both the ejector inlets and outlet. More detailed description of used installation will be presented during Conference. Whereas, Table 1 presents seven operating conditions which were implemented to the solver as the model boundary conditions. Each case contains similar parameters to compare the considered configurations.

Table 1: Typical operating conditions for supermarket refrigeration system employed in the numerical model as boundary conditions.

No.	Configuration	Motive nozzle inlet conditions		Suction nozzle inlet conditions		Outlet conditions
-	-	Pa	K	Pa	K	Pa
I	EJ1	7181500	299.3	2827628	275.9	3541842
II	EJ2	7227343	299.2	2819807	278.2	3547360
III	EJ1 + EJ2	7185919	299.2	2804615	275.4	3558447
IV	EJ3	7169179	299.4	2808163	274.8	3567226
V	EJ1 + EJ3	7087880	298.9	2808853	274.1	3556429
VI	EJ2 + EJ3	7096075	299.2	2810127	273.7	3566378
VII	EJ1 + EJ2 + EJ3	7142111	299.3	2788241	273.2	3572308

3.5. Model validation

The model based on the HEM approach was originally developed and validated by Smolka et. al (2013) for one- and two-phase flow using literature data for R141b and experimental data from the SINTEF test rig for R744 (carbon dioxide), respectively. The model accuracy was evaluated on the basis of the mass flow rates and was typically within 10% to 15%. Moreover, the HEM approach was applied by Palacz et. al (2015) to the supermarket operating regimes for CO_2. This analysis resulted in a satisfactory comparison to the measured results that were performed using the dedicated test rig at the SINTEF laboratory. This numerical study clearly demonstrated the application region of the HEM approach for the two-phase flow of R744. Namely, the accuracy of the mass flow rate prediction in the motive nozzle was within 5% to 10% of the supercritical parameters at the gas cooler outlet. That study also found that the model accuracy decreased with the decreasing distance from the saturation line.

4. Results

The Mach number field for the Configuration #7, is presented in Figure 4. A beginning of the shock wave occurs in the nozzle throat what simultaneously indicates the supersonic area. Nevertheless in the mixing zone, it could be indicated that subsonic as well as supersonic flow area exist. The core flow around the ejector axis is dominated by Mach number higher than one. Meanwhile, the layer situated in surroundings of the mixer wall is characterised by the subsonic flow. Before the end of the mixer the region of supersonic tapers taking the shape of a cone. The whole diffuser works in the subsonic flow conditions (Ma<0.25) what leads to the required higher pressures at the ejector outlet. It is worth noting that the Mach number was not much higher at the outlet of the smallest ejector comparing to the EJ2 and EJ3 units. Moreover, it can be concluded that the Mach number field is of the same character for all the considered ejectors. This guarantees a stable multi-ejector module work even in the most complex configuration of the three ejectors working in parallel. Another field such as pressure and vapour quality distribution will be discussed during Conference.

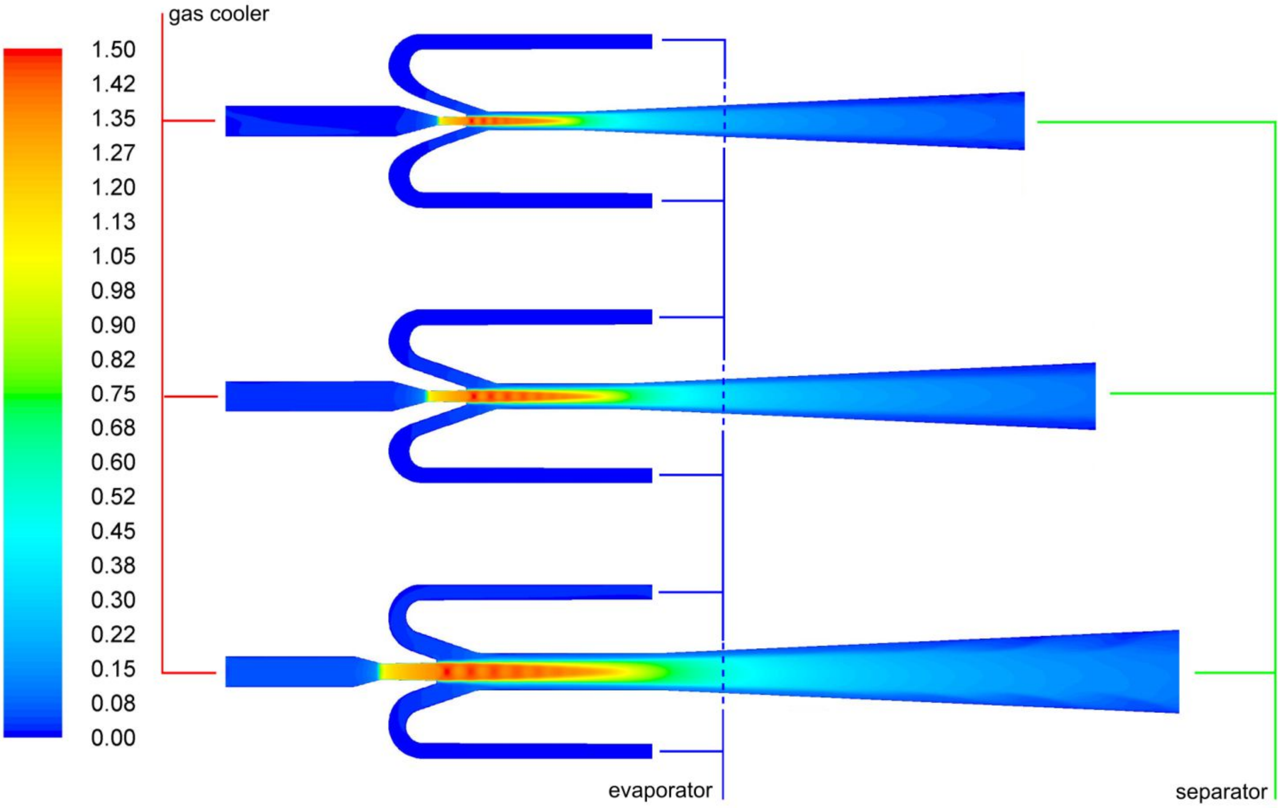

Figure 4: Mach number field obtained for Configuration #7 with the lines which indicate the collecting ducts from the gas cooler (red), evaporator (blue) and to the separator (green).

The most important results in the light of the module performance are presented in Table 2. The obtained mass flow rates show that the highest efficiency values could be ensured for the smallest cooling capacities. While the load of the multi-ejector module grew, the efficiency decreased by approximately 10% between Configurations #1 and #7. However, it is worth noting that the efficiency drop between Configuration #4 and #7 as well as MER were almost constant. Such a trend is considered as a very perspective one.

Nevertheless, the most important characteristic of multi-ejector module is described by the mass flow rates of the motive and the suction nozzles. An increment of these values indicates that the multi-ejector module is able to cover the required cooling load at high performance level. Furthermore, the mass flow rate difference between the considered configurations is gradual and small enough to ensure a flexible regulation. As it was mentioned, EJ2 was designed for twice higher MN flow than that of EJ1. EJ3 was prepared to cover twice of the EJ2 load. Moreover, the analysis focused on particular ejectors' streams will be presented during Conference. Further analysis of Table 2 shows that increments of the mass flow rate were generally constant when ejectors are paired into a parallel work. Such a situation occurred for both in MN and in SN mass flow rates. This almost linear character of covering the cooling load is very demanded for an efficient regulation of the refrigeration unit.

In order to validate these results, the simulated mass flow rate values were compared with the experimental data in a form of the relative errors presented in Columns 8-9 of Table 2. The difference between efficiency obtained from the experimental tests and numerical simulations are presented in a form of absolute error (percentage points) in Column 7 of this table. These errors are very small for the first two cases and then they slightly grow for the next configurations. Noticeable differences can be observed for the suction mass flow rate. This discrepancy can be explained taking into account the internal structure of the multi-ejector module and gradually increasing pressure drop with the unit load.

Namely, in module there are installed back-pressure valves with use of sophisticated geometry. Simplifications around these structures were provided for possibility of fully structural grid generation. This situation is equal to lack of pressure loses consideration in the numerical model so computed suction streams are higher than experimental. However, it is hard to precisely evaluate the level of pressure drop that actually occurs. Additional results of sensitivity analysis on pressure drop due to this phenomena will be presented during Conference.

Table 2: Comparison of the efficiency and the mass flow rate from numerical model and the experimental data.

No.	Configuration	Efficiency	MER	MN mass flow rate	SN mass flow rate	Validation results Efficiency	MN	SN
		%	-	kg/s	kg/s	p.p.	%	%
I	EJ1	45.2	0,274	0.0310	0.0085	4	-11	-2
II	EJ2	43.3	0,260	0.0630	0.0164	4	-12	-3
III	EJ1 + EJ2	40.7	0,247	0.0933	0.0230	5	-7	6
IV	EJ3	37.1	0,226	0.1224	0.0276	7	-4	20
V	EJ1 + EJ3	38.4	0,233	0.1519	0.0355	10	-2	33
VI	EJ2 + EJ3	37.7	0,231	0.1806	0.0416	10	-7	24
VII	EJ1 + EJ2 + EJ3	36.0	0,220	0.2132	0.0469	9	-5	28

5. Conclusions

The 3-D numerical analysis of the multi-ejector module have been performed. The obtained results show the character of the module work in seven configurations which cover the lowest capacities of refrigeration system. In each considered configuration, the module was characterised by a stable work and it covered required cooling capacity. The increase of the mass flow rate between these configurations confirms a precise regulation a potential using the module solution. Whereas, the results of particular ejectors mass flow rates will be presented during Conference.

During the analysis of the presented data, it could be stated that module efficiency decreased with the increasing cooling load what is related with the additional losses caused by the higher mass flow rates. Another reason is more intensive mixing process in the outlet collector.

Nevertheless, due to the very complicated physical phenomena in the multi-ejector module, the area of efficiency decrements as well as its improvement possibilities can lead to the shape optimisation of outlet collector. Chosen results of analysis on this collector will be presented during Conference. Moreover, further analysis would be focused on the more detailed evaluation of pressure losses along suction collector.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the Polish Norwegian Research Fund through project No. Pol-Nor/196445/29/2013.

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