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Multi-ejector concept for R-744 supermarket refrigeration

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ABSTRACT

Supermarkets are commercial buildings with major energy consumption and relatively large contribution to direct emissions of greenhouse gases through refrigerant emissions of the refrigeration and air condition system. The majority of the European systems are applying HFC-404A as working fluid. Average annual leakage rates in Europe are in the range of 15–20% of the total charge. Worldwide the figure is about 30% and HCFC-22 being the main refrigerant in use. Systems applying R-744 as the only refrigerant have been developed and more than 2000 supermarkets exists in Europe, mainly in northern and mid-European countries. However, the systems still have large potential in development with respect to energy efficiency, heat recovery and cost efficiency. In this paper efficiencies and capacities for an R-744 supermarket system layout with ejectors and heat recovery have been compared for different climate conditions. First results show relevant improvements in system efficiency of up to 30%.

Concept d'éjecteur multiple pour le froid au R-744 dans les grandes surfaces

Mots clés : R-744 ; CO_2 ; Supermarché ; Réfrigération ; Éjecteur ; Modelica

1. Introduction

Increased energy efficiency is the most efficient, the least expensive, and the least politically controversial path to a sustainable energy future: Energy saved does not cause emissions, and energy not used reduces the need for new controversial power plants and expensive distribution infrastructure. The International Energy Agency (IEA) states that energy efficiency measures will have to account for more than half of the sum of all measures required globally to avoid unacceptable global warming in our century (World Energy Outlook, 2012). This makes energy efficiency the most important climate issue of our time: Even if we should win the

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Nomenclature

A	Area (m^2)
a	Ambient
COP	Coefficient of performance (–)
Comp	Compressor
eff	Efficiency
Ej	Ejector
EV	Expansion valve
FGB	Flash-gas bypass
GC	Gas cooler
HP	High pressure
IC	Inter-stage cooler
IHX	Internal heat exchanger
i	Number index
LP	Low pressure
LT	Low temperature
MT	Medium temperature
MP	Medium pressure
SP	Separator
sc	Subcooling
$\dot{m}$	Mass flow rate (kg s^{-1})
p	Pressure (10^5 Pa)
Q_0	Relative cooling capacity (%)
T	Temperature (°C)
Greek	
η_{ej}	Ejector efficiency (–)
ρ	Density (kg m^{-3})

battles on Renewables, Biofuels and Carbon Capture and Storage, we would lose the war on global warming unless energy efficiency is substantially increased.

The European Union climate and energy targets for 2020, known as the "20-20-20" targets, set three key objectives for 2020: 20% reduction in EU greenhouse gas emissions from 1990 levels, raising the share of EU energy consumption produced from renewable resources to 20%, and 20% improvement in the EU's energy efficiency. Lately, the European Commission has looked at cost-efficient ways to make the European economy more climate-friendly and less energy-consuming. Energy efficiency will be a key driver of the transition. By moving to a low-carbon society, the EU could be using around 30% less energy in 2050 than in 2005 (Roadmap2050, 2011).

The main energy consumer of a supermarket is according to Nordtvedt et al. (2012) and Rhiemeier et al. (2009) the refrigeration system with about 50% and the heating system with about 20% of the overall annual energy consumption. In order to reduce the overall energy consumption special attention should be paid to the optimization of the refrigeration and heating system.

Therefore, this paper describes a calculation method to calculate efficiencies and capacities for two different supermarket system layouts. The adoption of non-controlled ejectors and additional functions such as heat recovery are evaluated in order to improve the energy efficiency of the system. Results of existing studies show relevant improvements in R-774 system efficiency when heat recovery has been adopted (e.g. Denecke and Hafner, 2011; Colombo et al., 2012; Karampour et al., 2012). Compared to other refrigerants R-744 is particularly suitable for heat recovery applications due to its operation mode close to the critical point.

Ejector usage is not applied at the moment. Thus, a theoretical analysis applying the modelling language Modelica has been carried out in order to investigate an R-744 multi-ejector system compared to a reference R-744 booster system for different European climates.

In order to investigate the multi-ejector system in a further study also experimentally the simulation models in this work used for the evaluation of efficiencies and capacities represent a laboratory test facility for a supermarket refrigeration and heat recovery system with downsized components.

In the first section a literature review about ejector technology in supermarket applications is given. In the following part a downsized multi-ejector test facility for a supermarket cycle is specified. The main part describes basically the simulation models of a one stage reference and multi-ejector system representing a supermarket test facility that were used for the computer simulation carried out in this paper. Additionally, the ejector design and efficiency measurements on a test rig are presented. Subsequently boundary conditions like climate data and load profiles and control concepts are shown. The simulation results are presented and finally the main results are concluded and an outlook on further work completes this paper.

2. Ejector technology for supermarket applications

Two phase ejectors utilize partly the expansion work available when high-pressure refrigerant is throttled in a motive nozzle inside an ejector. In the chosen lay-out (Fig. 1), the ejector pumps the low-pressure mass flow of the evaporators to a higher pressure level into a separator. The kinetic energy of the motive flow is applied to accelerate the refrigerant flow downstream of the evaporators. In the mixing chamber of the ejector both fluid flows equalize their velocities. This leads to a higher pressure level, compared to the suction pressure, inside the diffuser of the ejector. The primary fluid enters from the high pressure gas cooler side and the secondary fluid from the evaporator side; at the ejector outlet the mixed flow converges to a liquid separator.

According to Elbel (2011, 2007), Drescher et al. (2007), Banasiak et al. (2012), Fiorenzano (2011) and Lucas and Koehler (2012) R-744-ejectors may improve the system efficiency by up to 15%, depending on the ambient temperature of the heat rejection device of the refrigeration system.

Different multi stage R-744 supermarket refrigeration systems were investigated in the past e.g. by Gernemann (2003), Kruse and Schiesaro (2002), Fröschle (2009) and Sawalha (2008) but no ejector system in a supermarket application can be found in literature.

Based on previous investigations and on-going projects as Hafner et al. (2012), the system design concepts for ejector systems were developed, which can be applied for R-744 heat pumping systems. Initial system simulation results have shown that the performance (COP) of supermarket refrigeration systems equipped with a multi-ejector R-744 system

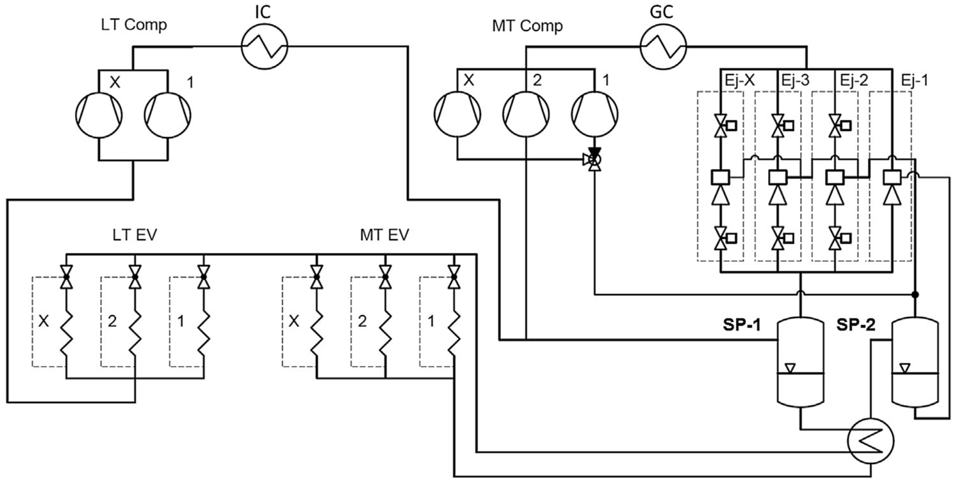

Fig. 1 – Circuit diagram of supermarket refrigeration and heating system with multi-ejector R-744 concept with non-continuously controllable ejectors.

increases significantly by up to 20%, at high ambient temperature or high return temperature from the heat recovery system. The excellent performance of R-744 systems at low ambient temperatures can also be maintained with the ejector system. Therefore, a significant improvement of the energy efficiency of future supermarket systems can be expected when applying R-744 and a multi-ejector solution. This system concept can be applied in the northern part of Europe as well as in the Mediterranean region. The concept can be applied for other R-744 vapour compression systems which do have efficiency challenges at high ambient (refrigerant return) temperatures, such as heat pumps for space conditioning and high water temperatures, mobile applications (truck & containers) and chillers.

Fig. 1 shows the multi-ejector R-744 system with non-continuously controllable ejectors. The presented system shows the most important part of the supermarket refrigeration system, which maintains the temperature inside the cooling cabinets. Heat from the freezing part of the system is rejected to the medium temperature part. From this part the heat is released to the different heat recovery units and external heat rejection devices (schematically shown as gas cooler GC and inter-stage cooler IC) before the refrigerant enters the expansion devices. In this case the ejectors replace the ordinary expansion valves which do not recover the expansion work.

The novel R-744 commercial refrigeration system solutions including non-continuously controlled ejectors with different ejector geometries allow applying standardized ejectors. With different cross sections in the motive nozzles the high side pressure can be controlled in accordance to the ambient temperature or load requirements. The MT compressors are sucking from the gas phase of the first separator (SP-1) downstream of the ejectors. The ejectors are applied to maintain a certain pressure difference between the separator (SP-2) and the separator (SP-1). In case of a reduced pressure lift capability of the ejectors, one of the MT compressors (rpm-controlled) can be connected to the vapour outlet of the separator (SP-2) and thereby reduce the entrainment ratio. This supports the ejectors in operation to maintain a certain flow rate of refrigerant via the ejector into the separator, even at low high side pressures. This solution secures a constant pressure difference between both separators.

3. Test rig facility for refrigeration system with ejector

Fig. 2 shows the circuit diagram of the test rig facility for the refrigeration system with multi-ejector concept. The size of the components is accordingly downsized. All heat exchangers are performed as plate heat exchangers and glycol is used as secondary cooling and heating fluid. In order to simplify the system the low temperature evaporator and compressor stage is omitted. The theoretical model and the simulation results presented within this work are a preliminary study for the experimental work and describe a downsized supermarket system.

4. Simulation models

In order to calculate the efficiencies and capacities of an R-744 supermarket system with a multi-ejector system a simulation model was used to compare both a reference system and the ejector system.

The programming language Modelica and the programming environment Dymola were used to simulate the dynamic systems with fast changing ambient conditions like for example ambient temperature and cooling and heating load controlled by implemented dynamic controllers.

Basis for the modelling was the component library for thermodynamic systems called TIL-Suite developed in cooperation with the company TLK-Thermo GmbH and the Institute für Thermodynamik in Braunschweig. The TIL-Suite is an advanced Modelica library for transient simulation of fluid systems such as e.g. heat pump, air conditioning, refrigeration or cooling systems. The library is the result of long term

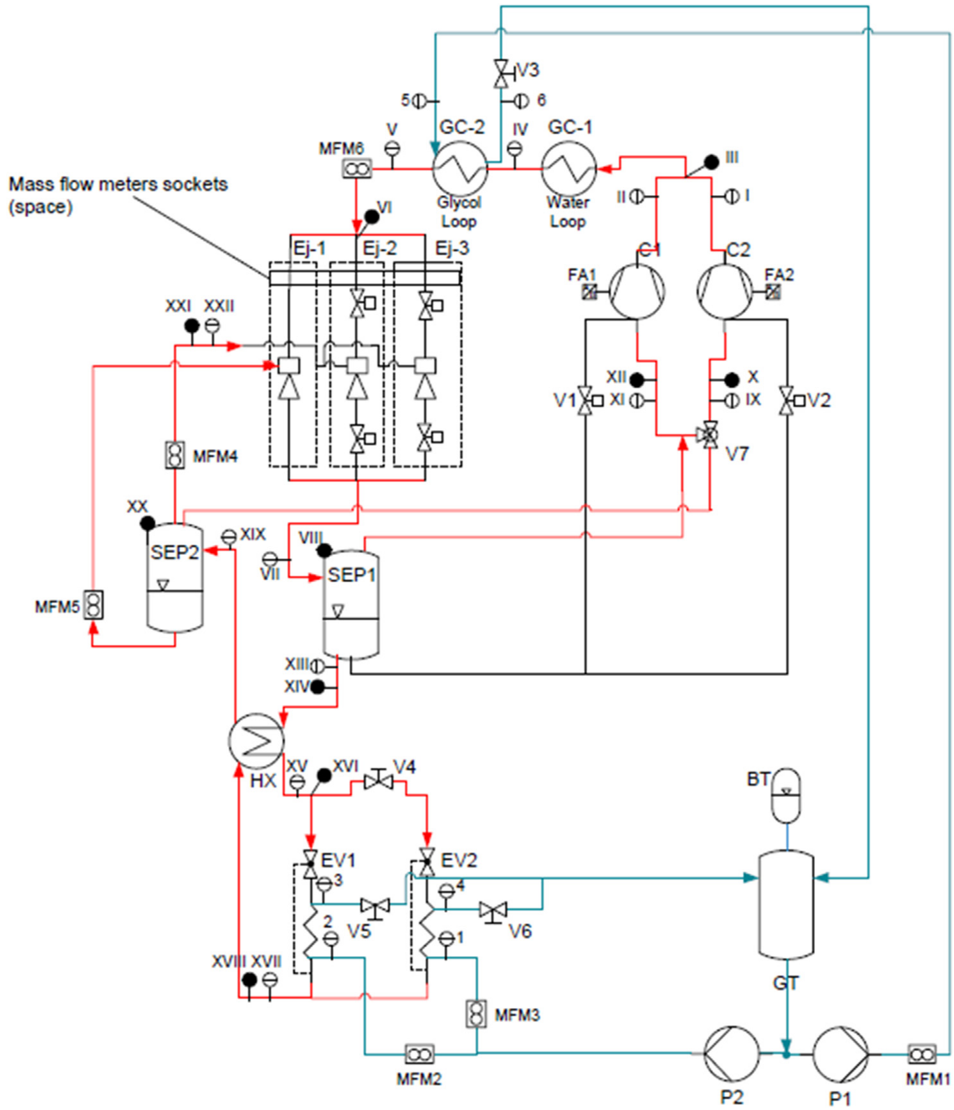

Fig. 2 – Circuit diagram of multi-ejector test rig facility.

experience in thermal science, simulation techniques and software design.

Richter (2008) examines existing libraries and proposes a new component model library that strictly aims on good readability and usability. The TIL library is a follow-up of the library described by Richter. A sustainable object-oriented structure was developed, which meets the demands of model developers, simulation specialists and design engineers. The TIL library was developed and maintained by TLK-Thermo GmbH and by the Institut für Thermodynamik at the TU Braunschweig (Tegethoff et al., 2011).

TIL provides a component library for compressors, heat exchangers, valves, tubes among many other components. For the implementation of the ejectors, plate heat exchangers and the controllers AddOn libraries were used and expanded due to the specific modelling requirements.

For the simulation of the property data of the fluids refrigerant, glycol, water and moist air the TILMedia Suite is used, which allows besides using own data the embedding of REFPROP and other fluid properties for the simulation. For the direct visualization of the simulation results the StateViewer was used as a direct interface to plot both the process data in p,h- and T,s-diagrams and furthermore the temperature distribution of the heat exchangers.

The program TILFileReader is used to read external data as boundary input for the cycle simulation like daily ambient temperature and cooling load. The climate data generated with the external meteorological databases METEONORM (Remund et al., 2010) is loaded during the runtime into the simulation model using the program TILWeatherClient.

First a system model was designed to simulate the state of the art of an existing two stage R-744 supermarket cooling and heating system (Booster System).

The simulation results presented in this study are generated by two simulation models for a supermarket test rig with downsized components: the first model represents the one stage reference system and the second model represents the one stage multi-ejector system.

4.1. *Reference-system – R-744 booster system with heat recovery*

Fig. 3 shows a two stage R-744 booster system with flash gas bypass valve, with evaporators on two different temperature levels and heat recovery (Fröschle 2009 and Javerschek and Hieble, 2011). The system is provided with an intermediate liquid/gas separator on a medium pressure level. The liquid coming out from the separator is subcooled by an internal heat exchanger and is expanded to two different pressure and temperature levels according to the chilled and frozen product cabinets: the medium evaporation pressure level for the medium temperature cabinets (MT) at 28 bar/−8 °C and to the low evaporation level pressure for the low temperature cabinets (LT) at 12 bar/−35 °C. The gas coming out from the separator is expanded by the flash gas bypass valve (FGB) to the medium evaporation pressure level and is directly compressed by the medium pressure compressors. The gas cooler is split into three gas coolers: Accordingly to the different temperature levels heat recovery, production of hot water, floor heating and the operating of geothermal borehole storage can be carried out (Titze, 2012). For each stage two compressors in parallel are implemented one with fixed rpm (50 Hz) and one with variable rpm control. About 80% of the overall cooling capacity is provided for the MT cabinet evaporators and less than 20% for the LT evaporators.

Fig. 4 shows the Modelica/TIL simulation model scheme for the R-744 reference supermarket test facility. In the test facility only the MT cabinet evaporators are considered that provide 80% of the cooling capacity. The reference system is a booster system with flash gas bypass with only one evaporator pressure level for the middle temperature cabinets. To simplify the investigated system only two gas coolers on the high pressure side are considered. In the test facility a water/glycol mixture is used as secondary fluid for the evaporators.

Four main controllers are used for the system controlling of the reference system: The cooling load of the MT cabinets is controlled by the compressor rpm. A high pressure control for the transcritical operation conditions is realized by the HP valve. For subcritical conditions a subcooling control is implemented. The medium pressure in the separator is controlled by the FGB valve and the superheat in the MT cabinet evaporators is controlled by a superheat control realised by the MP valves.

4.2. *Multi-ejector-system*

Fig. 5 shows the Modelica/TIL simulation model scheme for the supermarket test rig with multi-ejector system. Similar to the reference system shown in Fig. 4 the ejector test facility presented in Fig. 2 is designed as a simplified one stage booster system with water/glycol/R-744 plate heat exchangers. In contrast to the reference system the MT cabinet evaporators in the multi-ejector system have no superheat control but are designed as flooded evaporator system with outlet quality of 95%. Therefore, a low pressure receiver (SP 2) is installed between the internal heat exchanger (IHX) and the ejector suction port. In the test facility the separator filling level and therewith the vapour ratio can be controlled by the MP valves.

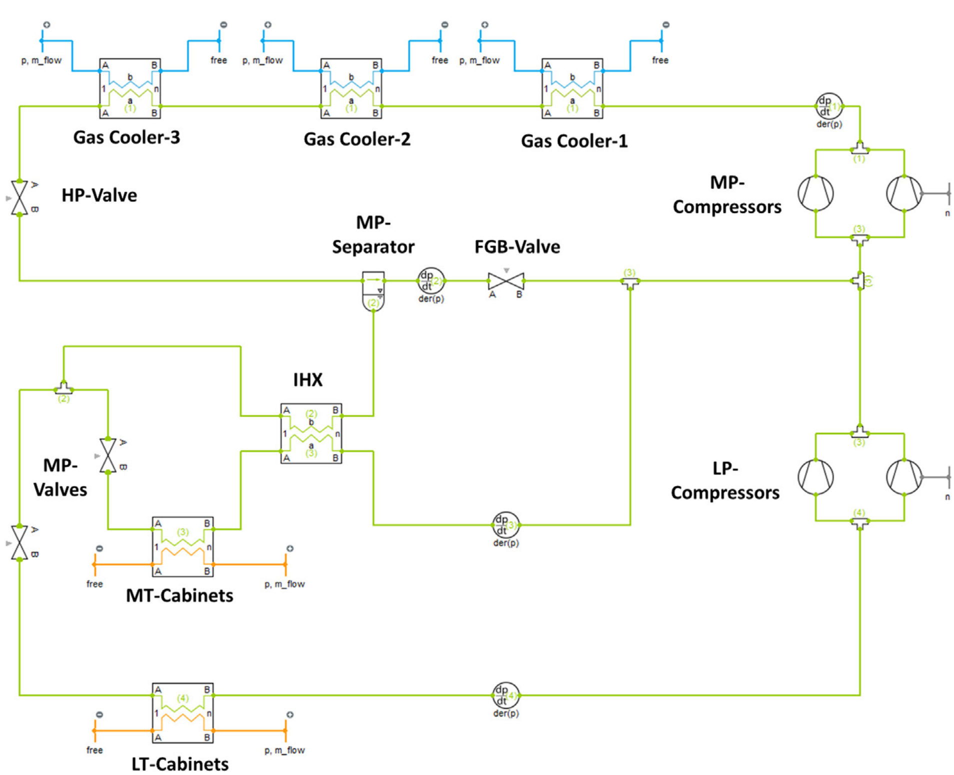

Fig. 3 – Modelica/TIL simulation model scheme of the R-744 supermarket refrigeration and heating system. Two stage booster system with flash-gas bypass valve for chilled (MT) and frozen (LT) products.

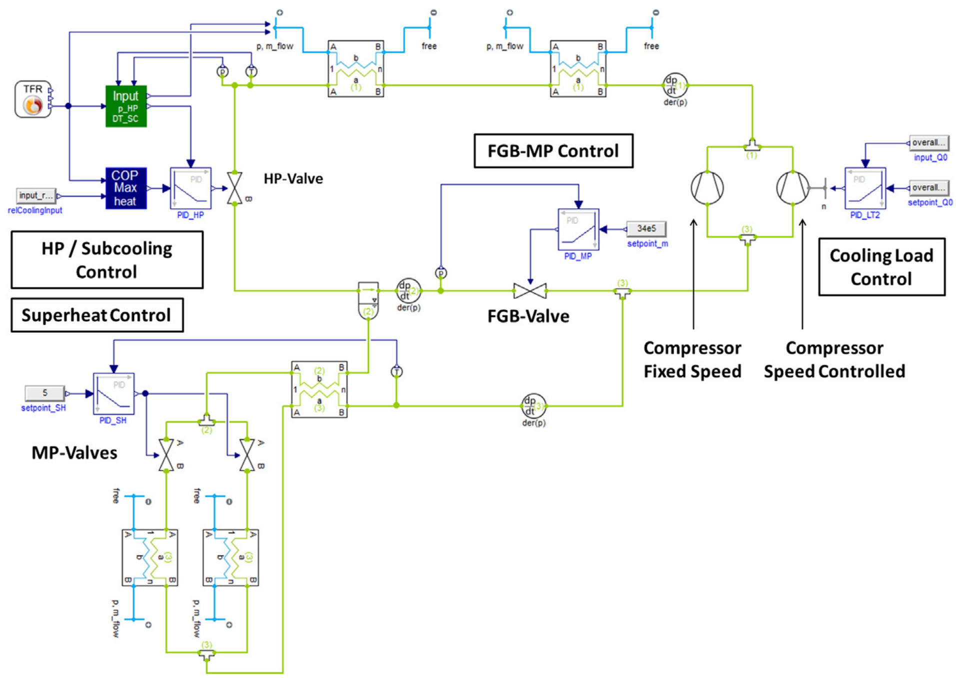

Fig. 4 – Modelica/TIL simulation model scheme for the R-744 reference supermarket test facility. Simplified one stage booster system with flash-gas bypass, water/glycol heat exchangers and controllers.

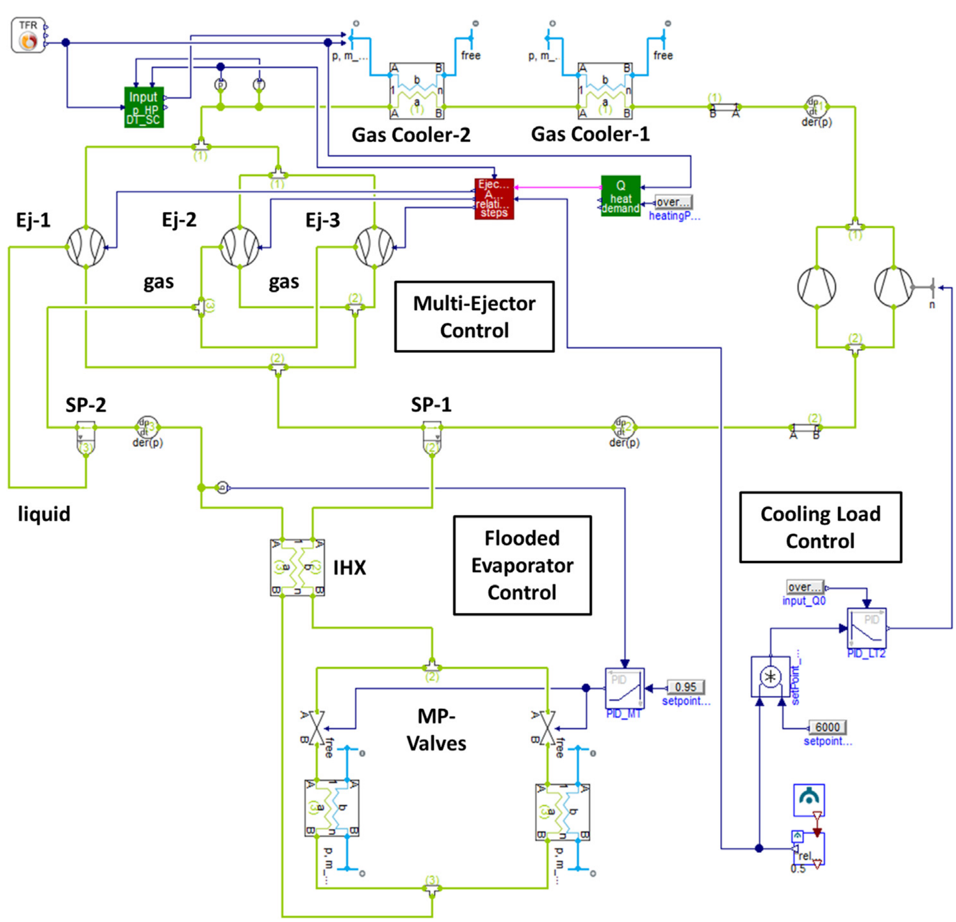

Fig. 5 – Modelica/TIL simulation model scheme for the supermarket test rig with multi-ejector system. Simplified one stage booster system with water/glycol heat exchangers.

The outlet vapour ratio of the evaporators will be set by a controller that manipulates the valve opening. The vapour ratio can be set according to the filling behaviour of the separator. In the simulation model the controlling is realized by a PI controller and a vapour ratio sensor with a setpoint set to 95%.

To meet different cooling and heating load requirements in full load and part load operation mode three ejectors with fixed driving flow nozzle cross section area are placed in parallel. Ejector 1 is permanently in operation and connected with the liquid port of the separator. Ejector 2 and ejector 3 are connected with the gas port of the separator and connected with two-way valves in such a manner that a connection and disconnection of all three ports is possible in order to use one, two or three ejectors in parallel. The suction pressure of the MP compressors in the investigated ejector system is higher compared to the reference system due to the pressure lift of the ejector. This means for the LP-compressors in the real ejector system that the outlet pressure will be higher compared to the reference system. This additional compressor work of the ejector system is neglected in this investigation. Here has to be noted that only 20% of the cooling capacity is provided in the LT cabinets.

4.3. *Reference system control and ejector design*

A variation of the high pressure at different ambient temperatures was carried out (Fig. 6) in order to design a COP optimized controlling strategy for the reference system. For the transcritical area the maximum COP can be set by the high pressure valve due to the corresponding high pressure that is a function of the ambient temperature. In the subcritical area a subcooling controller can be used to achieve a high COP.

The maximum cooling COP for the investigated reference system achieved for an ambient temperature of 25 °C equals 2.75. Similar COP values are presented by Sawalha (2008) and Finck et al. (2011) for R-744 and R-404A supermarket systems.

Within the scope of this work an ejector prototype was designed and measurements were carried out to identify pressure lift and efficiency for boundary conditions that are typical for a supermarket refrigeration system (Fig. 7). In total 80 different measurement points were scrutinized. The measured pressure lift shows values between 2 and 6 bar and the ejector efficiencies defined in Fiorenzano (2011) and Köhler et al. (2007) are in the range between 10% and 27%. The average value for the ejector efficiency is about 20%. The outlet pressure was varied slightly below 40 bar even though the typical intermediate pressure in the supermarket system is lower than 35 bar. Ejector measurements presented by Lucas and Koehler (2012) show ejector efficiencies at 34 bar suction pressure that are slightly higher than 20%.

The geometry of the multi-ejector system using three ejectors in parallel was designed as follows: in the first step simulations with the ejector system using one theoretical ejector model with variable flow area was used to calculate the overall driving nozzle flow area for COP optimized operating conditions in dependency of the ambient temperature. Theses simulations were carried out with an efficiency based model using the Bernoulli equation as mass flow equation for the driving nozzle:

$$\dot{m} = A_{\text{eff}} \cdot \sqrt{2 \cdot \varrho_{\text{in}} \cdot \left(p_{\text{driving}} - p_{\text{suction}}\right)}. \tag{1}$$

For different cooling loads and ambient temperatures the overall effective driving nozzle area due to the maximum COP was determined (Fig. 8). The ejector efficiency was set to a constant value of 20% for all simulations carried out within this paper.

The result of this investigation can be seen in (Fig. 8, left side) and shows that an almost constant overall effective

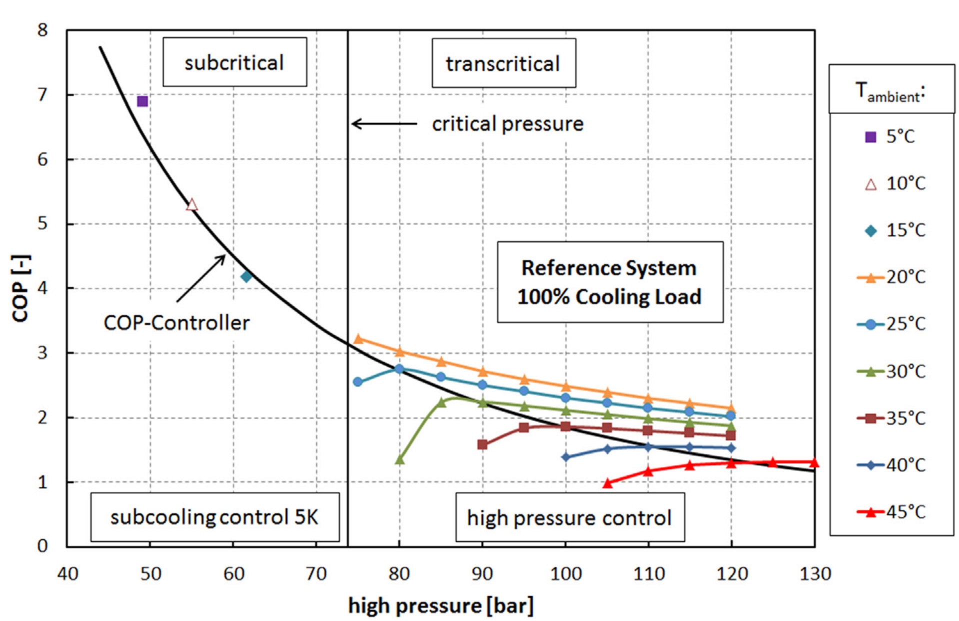

Fig. 6 – COP for cooling modus plotted versus high pressure for the reference test rig. In the transcritical operation modus (right side) the high pressure is set due to the maximum COP. On the left side the high pressure is a result of a constant subcooling control.

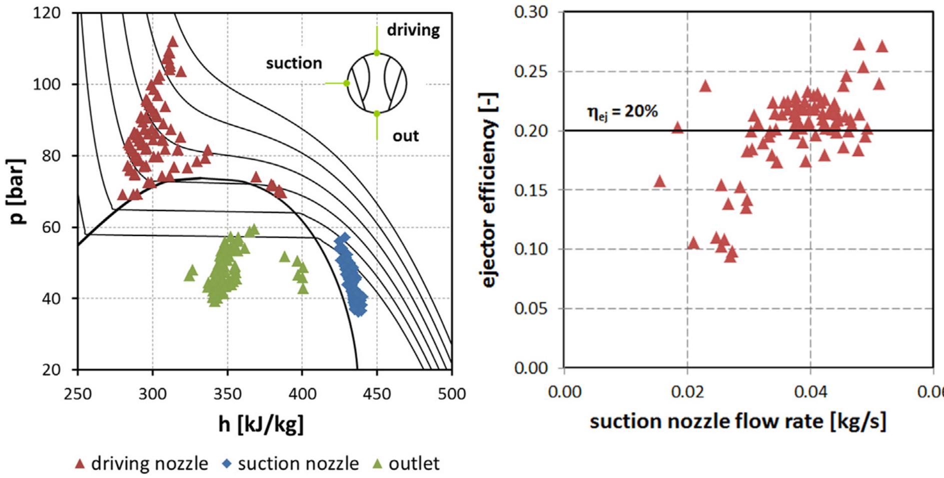

Fig. 7 – Measurement data of investigated prototype ejector in p,h-diagram (left side) and efficiency plotted versus suction flow rate (right side).

nozzle area can be obtained for each cooling load (horizontal lines). The increase of COP by using a refrigeration system with ejector depends significantly on the ambient temperature and increases with increasing ambient temperature from about 10% at 10 °C to up to 20% at 45 °C. Based on these simulations the multi-ejector system was designed and the driving nozzle flow area of each ejector was optimized.

5. Boundary conditions and controlling

In order to investigate the annual energy consumption of a supermarket for different climate zones three typical locations were chosen; Athens representative for Mediterranean, Frankfurt with Middle European and Trondheim with typical North European climate. For each location long-time averaged climate data were selected for 4 typical days in summer, fall, winter and spring. Fig. 9 shows the average ambient temperature for every half hour for an averaged 18th of August, 13th of October, 12th of January and 14th of April. The climate data are calculated based on the meteorological database METEONORM (Remund et al., 2010). Alternatively the climate data for a complete year can be used for a more comprehensive simulation.

A typical daily profile for the relative cooling load that was used for all simulations independent from season and location is shown in Fig. 10 left. The relative heating demand within this simulation in this study is proposed to be proportional to the temperature difference to the ambient (Fig. 10, right). The relative cooling and heating load is defined as the ratio of the actual load referred to the maximum load at the design point.

The reference system is controlled by a high pressure and a subcooling control. A set point function was chosen for each

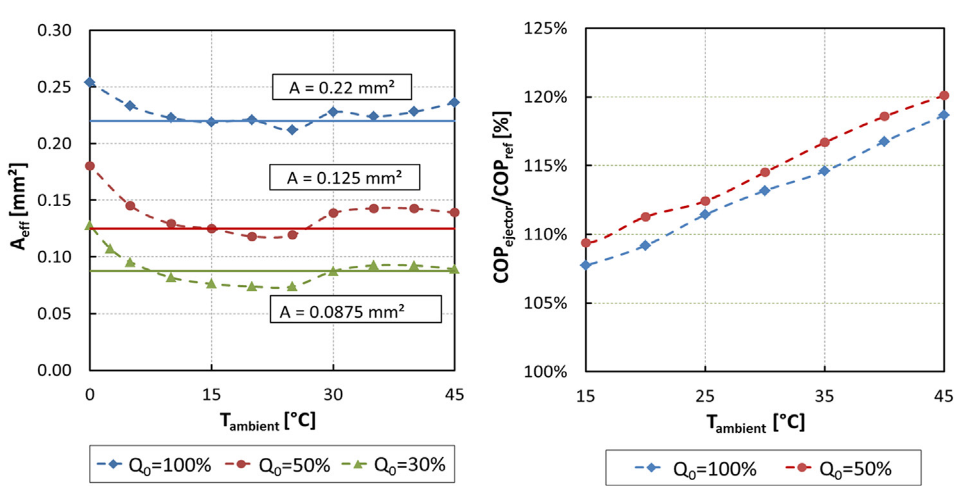

Fig. 8 – Simulated effective flow area of the ejector driving nozzle due to maximum cooling COP for 100%, 50% and 30% cooling load versus ambient temperature for a constant ejector efficiency of 20% (left side). Cooling COP increase plotted versus ambient temperature for the ejector system compared to the reference system (right side).

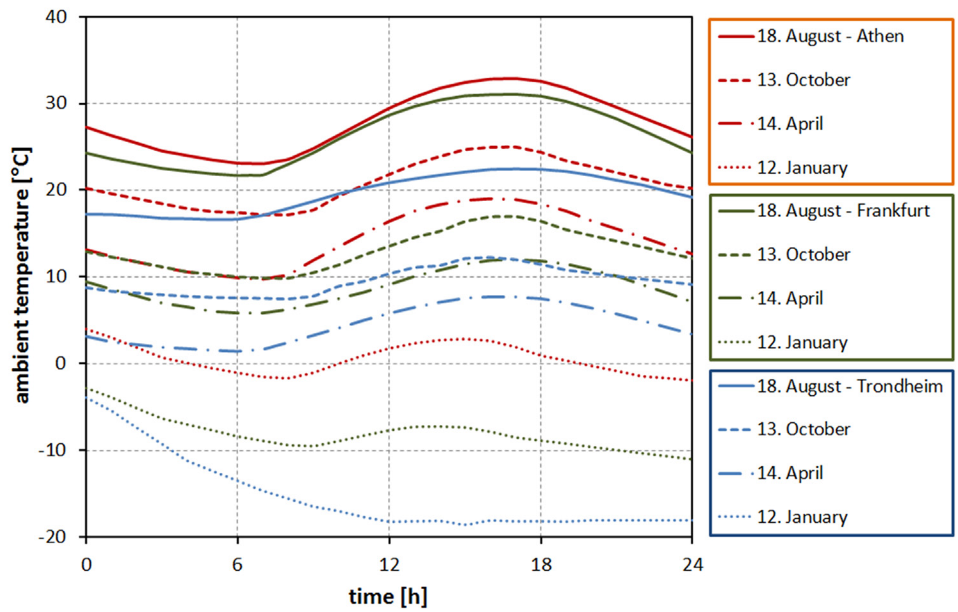

Fig. 9 – Daily temperature variation of average ambient temperature for different seasons and locations from METEONORM databank (Remund et al., 2010).

operating mode heating and cooling depending on ambient temperature, cooling load and heating demand:

$$p_{HP}/\Delta T_{SC} = F\left(T_a, \dot{Q}_{Cooling-Load}, \dot{Q}_{Heating-Demand}\right) \quad (2)$$

In order to control the multi-ejector system a functional relation was chosen to calculate the effective nozzle cross section in dependency of ambient temperature, cooling load and heating demand:

$$A_{eff-EjectorDrivingNozzle} = \sum_i A_i = F\left(T_a, \dot{Q}_{Cooling-Load}, \dot{Q}_{Heating-Demand}\right) \quad (3)$$

If the ambient temperature is lower than 15 °C the heat recovery is used to heat the supermarket. If the heat capacity from the heat recovery is not sufficient to match the heat demand the high pressure is increased (heating mode) and if the heat capacity is higher than the heat demand the high pressure is set to a lower value due to refrigeration (cooling mode). The evaporators in the reference system are controlled by a superheat control. The evaporators of the ejector system are designed as flooded evaporator system with vapour ratio control.

In the first step a simplified control strategy using the functions from Equations (2) and (3) was chosen in order to carry out a first set of transient system simulations and to discuss the typical system behaviour for the ejector system compared to the reference system. Therefore both systems are not working in all cases in optimized working conditions and the high pressure is not set generally to identical values for both systems. The investigation of systems with optimized control strategies is planned in further work.

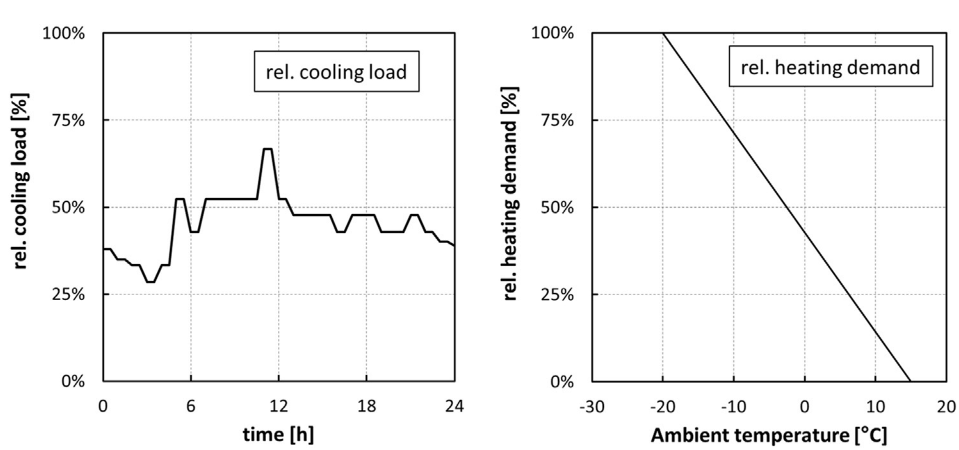

Fig. 10 – Typical rel. cooling load profile (left side) and rel. heating demand for a supermarket as linear function of the temperature difference to the ambient (right side). The rel. cooling and heating load is defined as the ratio of the actual load referred to the maximum load at the design point.

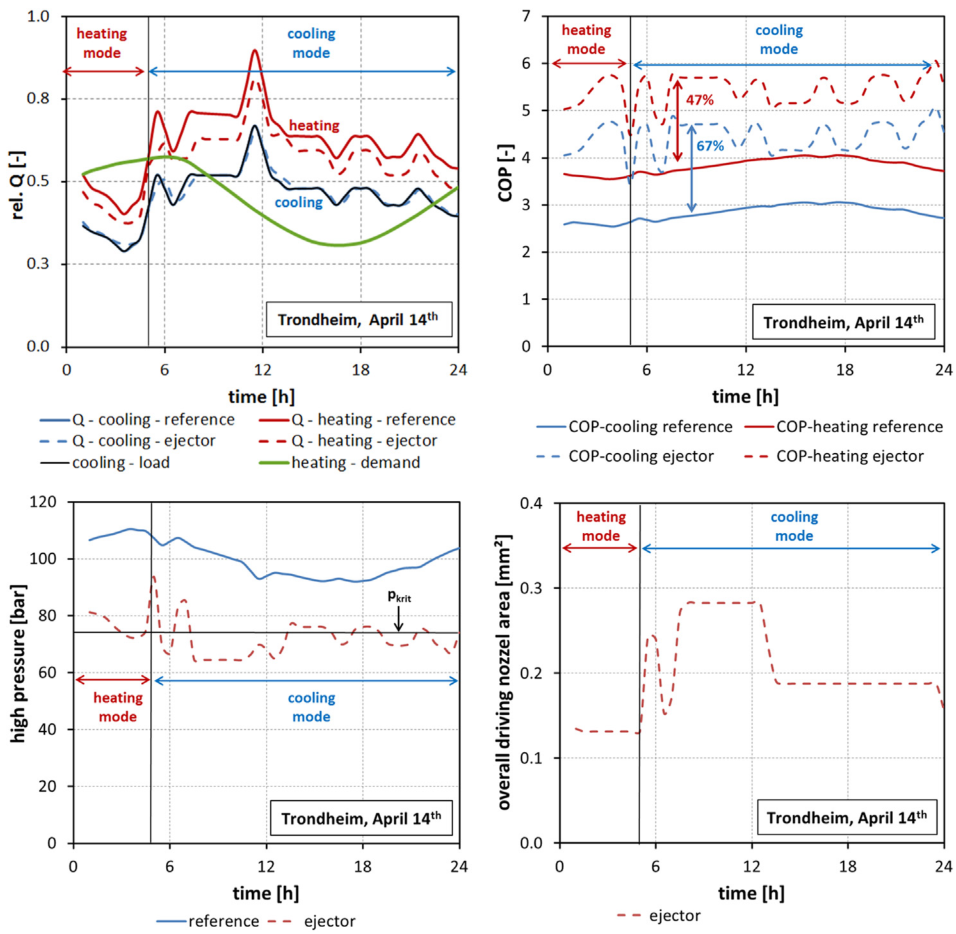

Fig. 11 – Transient simulation results for one day based on averaged climate data of a typical 14th of April in Trondheim. *Top left*: cooling and heating power of the reference and ejector system and cooling load as well as heating demand. *Top right*: COP for heating and cooling for reference and ejector system. *Down left*: high pressure for reference and ejector system. *Down right*: overall effective flow area of the activated ejector driving nozzles.

6. Simulation results

In the following section typical results of the dynamic simulation using the simulation models, boundary conditions and a simplified control strategy as described above are presented and discussed. Therefore two different simulation models for the supermarket test rig with downsized components were used: the first model represents the one stage reference system (Fig. 4) and the second model represents the one stage multi-ejector system (Fig. 5). A simplified control strategy was chosen in order to carry out a first set of transient system simulations.

In the first step transient results such as diurnal variation of the system variables and in the second step averaged results are presented. For the evaluation of the systems cooling and heating efficiency the following coefficients of performance are defined as follows:

$$COP_{cooling} = \frac{\dot{Q}_o}{P_{Comp}} \quad COP_{heating} = \frac{\dot{Q}_{heating}}{P_{Comp}} \tag{4}$$

The dynamic simulation results for an averaged 14th of April at the location in Trondheim for both the reference and the multi-ejector system are presented in Fig. 11. Both systems can provide accurately the needed cooling load corresponding to the load profile in Fig. 10 according to the compressor rpm control. The heat demand for the supermarket in the morning between 00:00 am and 5:00 am is higher than the heat provided by the heat recovery system for both the reference and the ejector system. This results from the low cooling load (Fig. 10) and the low ambient temperature (Fig. 9) during the night. Therefore, the controller sets the high pressure of the reference system to a supercritical value of about 110 bar in order to get as much heat power as possible (heating mode). This leads to an operation mode that is not COP optimized for the cooling case. In this time frame the multi-ejector system is only working with one ejector with the smallest driving nozzle area in order to get the high pressure as high as possible. However the COP of both the cooling system and the heat recovery system can be increased by the multi-ejector concept between 30% and 90%.

It is important to note that the simulated ejector system due to its configuration and controlling shows in Fig. 11 down left a lower curve for the high pressure compared to the reference system so that the comparability is not ensured completely. The heat demand for the rest of the day is more

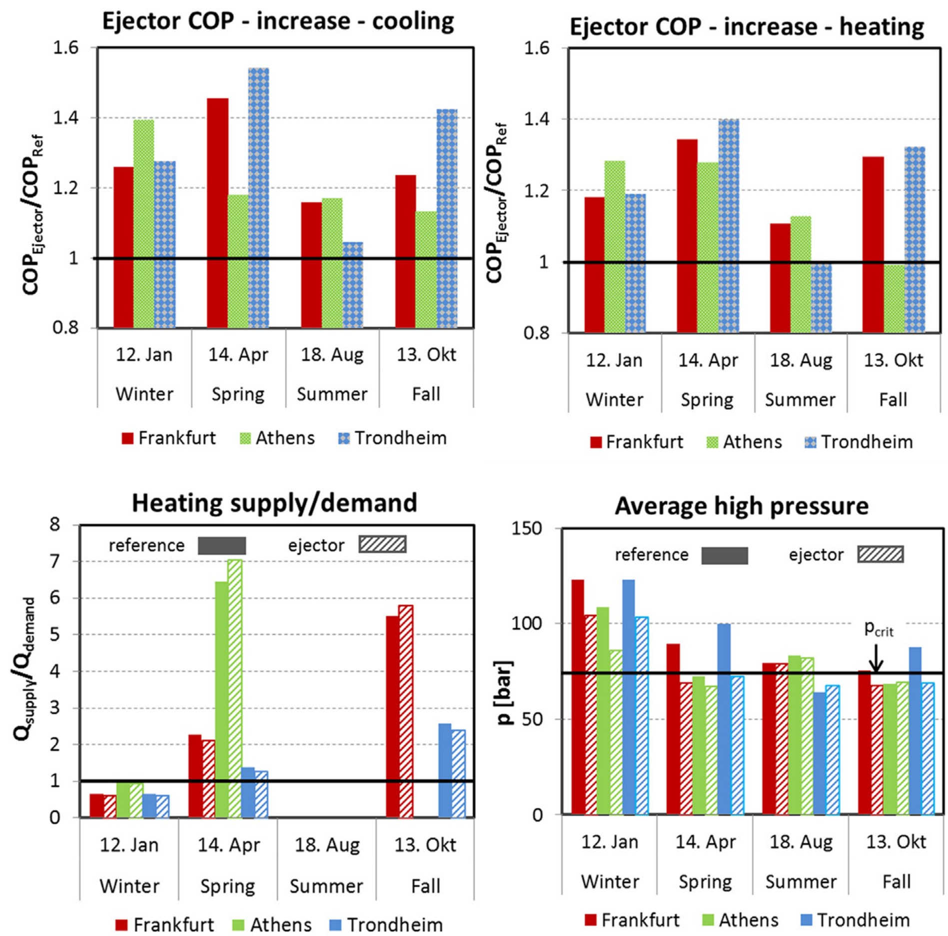

Fig. 12 – Averaged simulation results for one day based on averaged hourly climate date of a typical Winter, Spring, Summer and Fall day for three different climates in Frankfurt, Athens and Trondheim. *Top*: relative COP improvement due to the ejector compared to the reference system. *Bottom left side*: ratio of produced heat power and demand. *Bottom right side*: average high pressure for reference and ejector system.

than covered. The results show, that the high pressure of the reference system could be further reduced for the cooling modus and be further raised for the pure heating modus. Both systems can be optimized concerning their system and control configuration. This also shows that the COP-increase of the ejector system is closely related to the control concept of both systems. It shows also that this kind of systems with an active heat recovery strategy will profit from an intermediate heat storage, which decouples the refrigeration plant from the heating system of a supermarket.

The average daily values for the rel. COP increase due to the ejector system for cooling and heating power is plotted in (Fig. 12, *top*). The averaged ratio of produced heat power and the heat demand as well as the averaged high pressure is plotted in (Fig. 12, *bottom*).

For the averaged 14th of April (spring) at the location in Trondheim an increase of the COP of 40% (heating) and 50% (cooling) can be assessed. The daily averaged heat supply is about 40% higher than the demand.

In order to provide enough heating capacity via the heat recovery system on the 12th of January the high pressure is set by the controller to a supercritical value.

7. Conclusions

This paper presents efficiencies and capacities for an R-744 supermarket system layout with ejectors and heat recovery that has been investigated for different climate conditions. In the scope of this work simulation models for two supermarket refrigeration systems with and without ejector neglecting the low temperature cabinets were implemented using the Modelica/Dymola based simulation tool TIL-Suite.

A reference booster system with flash gas bypass and heat recovery and a similar system with a multi-ejector concept for a test rig facility are considered. In order to investigate the systems for different ambient temperatures and load conditions a first control concept was developed to operate the systems in working conditions for both refrigeration and heat recovery mode. The calculated COP of the reference system is similar to the values presented in literature.

Measurements carried out with an ejector prototype show that the pressure lift between 2 bar and 6 bar with an averaged ejector efficiency of about 20% can be reached. The multi-ejector system was designed based on cycle simulations with variation of the ambient temperature and the cooling load. Steady state cycle simulations carried out with an ejector model using a constant ejector efficiency of 20% show that the driving nozzle flow area for maximum COP depends basically on the cooling load. Compared to the investigated reference system a COP increase between 10% at 15 °C and 20% at 45 °C ambient temperature can be determined.

Average hourly climate data for each season and three different European climate zones for Mediterranean, middle and northern European climate represented by the cities Athens, Frankfurt and Trondheim are chosen to investigate the transient operation behaviour of the ejector system. Therefore the diurnal weather variations of four typical days corresponding to each season are used as boundary conditions.

Transient simulation results show that during days in spring and fall the system is switching from the optimized cooling mode to the heating mode in order to cover the heating demand.

To enlarge the heating capacity the high side pressure of the system is artificially increased by the control unit. During the winter season when the heating demand cannot be completely covered by the heat recovery mode the high pressure is set by the controller to supercritical values to produce a maximum amount of heat to the heating system.

For nearly all investigated boundary conditions the multi-ejector system shows significant COP increase compared to the reference system for both cooling and heating mode. The increase of COP depends highly on the system control strategy. Typical COP increase during the cooling mode of 17% in Athens, 16% in Frankfurt and 5% in Trondheim can be achieved during the summer. In the winter the typical COP increase is between 20% and 30%.

The analysis in this study is done for a single stage system and the additional compressor work in the low pressure compressor stage of the ejector system was neglected with the assumption that 80% of the cooling capacity is provided for the medium temperature cabinets and 20% provided for the low temperature cabinets only.

Future work should be done to optimize the system control strategy in respect to enlarge the energy efficiency for cooling and heat recovery in different climate zones. The implemented model can be extended for the two stage system and used to carry out detailed annual energy consumption simulations with climate data for a complete year in order to optimize the overall system, including an intermediate heat storage facility, to avoid peak demand operations.

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