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SMALL WATER EJECTOR CHILLER WITH ON-OFF OPERATED PUMP

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ABSTRACT

The article presents a small steam ejector refrigeration machine using R718 (water) as the refrigerant and powered by a low temperature heat source of 90°C. The objective of this course is the design and troubleshooting of a liquid refrigerant pump. Because of the thermal and physical properties of water, all components of the machine, including the pump operate in a deep vacuum. The high latent heat of water has a significant effect on the required refrigerant flow, resulting in increased demands on the refrigerant pump. One of the critical and practical problems of such design is implementation of a suitable small liquid pump where contradictory parameters are required - small but stable liquid flow at deep under pressure, reliability, long service interval, problematic cooling of pump electric motor and reasonable price. One of the solutions can be using of a pump working in combination with a pressure tank. In this concept the running time of the pump is controlled by the water level in the tank. The working characteristics of this cooling circuit solution are discussed.

Keywords: Refrigeration, Ejector Cooling Cycle, Refrigerant Pump, R178

1. INTRODUCTION

Cooling and air conditioning are crucial for human comfort, productivity, and health, especially as global temperatures rise due to climate change. As global temperatures increase, cooling systems become vital in many regions to maintain indoor air quality and comfort, reduce heat-related illnesses, and even preserve food and medicine. In warmer climates and during heatwaves, air conditioning can be lifesaving. Moreover, in densely populated urban areas, heat islands often exacerbate the ambient temperatures, further increasing dependence on cooling systems. As populations grow and urbanize, the demand for these systems has increased dramatically, leading to significant energy consumption worldwide. Air conditioning and cooling systems are among the largest consumers of electricity in homes and businesses, especially during peak load times. The energy demand for cooling is expected to continue growing, making energy efficiency a critical focus for manufacturers and policymakers. Implementing more efficient systems and technologies, improving building designs, and adopting more stringent standards and regulations are key strategies to manage this demand and reduce the associated environmental impacts.

Ejector cooling offers a promising alternative to conventional cooling technologies, particularly in terms of sustainability and energy efficiency. By using heat sources such as solar thermal energy, industrial waste heat, or even renewable energy, ejector cooling systems can significantly reduce electricity use. This technology not only helps in cutting down operational costs but also reduces the environmental footprint of cooling systems. Ejector cooling can be especially beneficial in remote or off-grid areas, where electricity is limited or unreliable. This capacity to harness renewable or otherwise waste energy sources means that ejector systems can provide cooling with much lower energy costs compared to traditional systems. Moreover, the simplicity of the design and the absence of mechanical compressors reduce maintenance costs and enhance the reliability of the cooling system. Ejector cooling systems have a minimal environmental footprint, particularly because they can operate effectively without the use of harmful refrigerants that are common in conventional air conditioning systems. Many traditional cooling agents contribute to global warming and ozone depletion when leaked into the atmosphere. In contrast, ejector systems can use natural substances like water and drastically reducing potential environmental hazards.

2. STATE OF THE ART

Exergetic analysis provides insight into how effectively ejector cooling systems utilize available energy. The research by Syed A. Tirmizi and colleagues in 2011 underscores that modifications in generator and evaporator temperatures can significantly enhance system performance. By raising generator and evaporator temperatures while lowering condenser temperature, the performance improvements observed achieved the highest coefficient of performance (COP) (Syed A. Tirmizi et al., 2011). Further comparative studies have demonstrated the influence of parameters like entrainment ratio and compression efficiency on ejector cooling cycles. These systems can improve energy efficiency by up to 26% over traditional compressor-based cycles, highlighting their potential as an alternative to conventional vapor compression cycles (J. A. E. Carrillo et al., 2017). Practical applications of this technology are also evidenced in solar-assisted ejector systems. A study by S. Varga in 2009, found that these systems can maintain acceptable efficiency with specific temperature conditions: generator temperatures not below 90°C, evaporator temperatures not below 10°C, and condenser temperatures above 35°C (S. Varga et al., 2009). Another study explored high-performance solar cooling systems, indicating that the design of ejector configurations significantly impacts efficiency. Larger mixing section areas lead to greater cooling capacity but lower condensing temperatures. Conversely, smaller nozzle output areas enhance reliability and repeatability, yielding higher condensing temperatures but lower cooling capacities (Yusuke Saito et al., 2014). A study focusing on the computational fluid dynamics (CFD) modeling of hydrocarbon ejectors for cooling systems presented new insights into optimizing ejector design to enhance performance. The findings showed that a small area ratio and converging-area chamber in hydrocarbon ejectors improve overall performance in hot climate applications, while other geometric design parameters have minor effects (Saleh B. Mohamed et al., 2022).

To further our understanding of ejector cooling systems, a 2019 study examined how varying generator pressures impact air cooling systems. Their theoretical analysis showed that higher generator pressures could enhance the performance of thermal ejectors, generating stronger shock waves and increasing cooling capacity, particularly beneficial during hotter periods (M. Ouzzane et al., 2019). An impactful paper by P. Pereira, shows that an advanced ejector which changes its geometrical features depending on the upstream and downstream conditions can increase the COP by 80% when compared to the performance of a fixed geometry ejector. Experimental COP values varied between 0.4 and 0.8, depending on operating conditions (Pereira et. al, 2015). Another publication shows the usage of multiple parallel arrays of ejectors, which can improve seasonal COP up to 85.0% compared to conventional systems and meet the required cooling load (F. Aligolzadeh et al., 2019).

On the practical side, another paper examined the first industrial application of an ejector refrigeration system using R1233zd(E), which is a refrigerant with low Global Warming Potential. This innovative study explores the system's operation with an ultra-low temperature heat source below 70°C, a unique application in industrial settings. The system achieves a mass entrainment ratio of up to 0.24 and delivers up to 45 kW of cooling capacity, with efficiency coefficients between 0.63 and 0.78. However, its efficiency is lower than systems using R1234zd(E) and isobutane (R600a) under comparable conditions, suggesting potential areas for hybrid system improvements (Gagan et. at. 2023). Studies on transcritical CO_2 shows that ejector expansion refrigeration cycle (EERC) can achieve up to 18.6% better cooling COP than internal heat exchanger cycles and 22.0% better than conventional vapor compression refrigeration cycles, with a proper ejector entrainment ratio. (Jianqiang Deng et al., 2007). Another study investigating ejector cooling cycle with R134 found out that the refrigerant performs well under superheated primary flow conditions, with a COP range of 0.59-0.67 and a constant pressure mixing ejector generating higher backpressure (B. Tashtoush et al., 2015).

3. DEFINITION OF THE REASEARCH SUBJECT

Our research focuses on the development of small and medium-sized decentralized refrigeration sources operating on the principle of ejector refrigeration cycle. In terms of cooling capacity, it is the area up to 30kW. The refrigerant we work with is fundamentally water (R718), mainly because of its ecological neutrality and availability. However, we are also considering a possible switch to propane (R290) in the future.

The design of our refrigeration cycle is based on the standard ejector refrigeration cycle circuit shown in Fig 1a. It contains a generator pump which ensures the flow of refrigerant from the low pressure to the high pressure side of the circuit. However, choosing a pump that fits the requirements of the cooling circuit, including output pressures, technical compatibility, and which has suitable overall construction in term of ease of integration, long lifespan, and it' operation does not support the formation of cavitation of fluid, is nearly impossible. The choice is further complicated by the price of this pump. There was no suitable commercially manufactured pump, mainly as the fluid at the suction is in a state close to saturated liquid. Also the requirement for a relatively high outlet pressure in combination with a small flow rate is not standard. In the end, a pump that met the discharge requirement, but significantly exceeded the flow was used. For this reason, we had to operate it in an switching on-off mode which was interfering with the condenser pressure. The evaporator has shown to be highly sensitive to these pressure changes, resulting in changes in the achieved cooling circuit parameters. For this reason, changes in the cooling circuit were designed and tested in order to operate the evaporator in optimum mode. As can be seen on Fig. 1a and Fig 1b, there are two options to ensure the water flow to the evaporator. One with „traditional arrangement ", where the flow of refrigerant to the evaporator is ensured by a pressure difference controlled by a throttling valve. In fact, this valve has been replaced by a vertical spacing between the evaporator and the refrigerant tank.

The generated hydrostatic pressure then provided the necessary pressure reduction. The other option (Fig. 1b) is to use a dedicated peristaltic pump, which in theory would stabilize the system. The solution also provides full control of the amount of refrigerant dosed to the evaporator, including its complete pressure separation from the condenser.

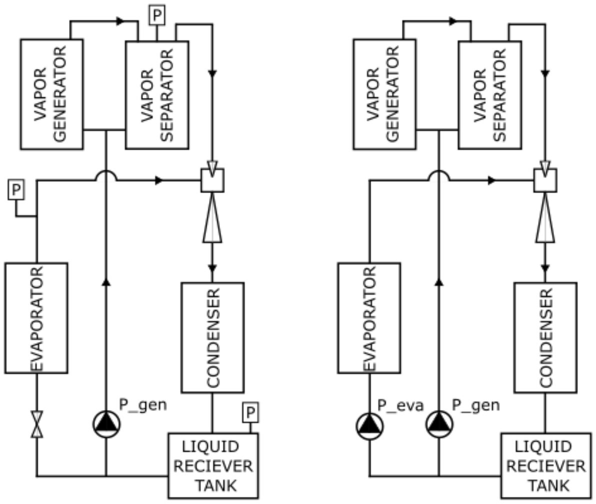

Figure 1: Schematic diagram of tested ejector cooling system a) pressure difference operated evaporator b) pump operated evaporator

4. DESCRIPTION OF THE EJECTOR COOLING SYSTEM (ECS)

The diagram of the ejector cooling system is on Fig.1. The system is located at the Slovak University of Technology, Faculty of Mechanical Engineering, and its purpose is to research the impact of individual parts, geometries, and connections on the overall performance of the system. Designed parameters of tested ejector cooling system are in Tab.1.

Table 1. Designed parameters of ejector cooling system

Cooling circuit		Ejector	
Cooling capacity	2.542 kW	Primary vapor flow	2.996 g/s
Heat input	6.915 kW	Secondary vapor flow	1.031 g/s
EER	0.368	Minimal nozzle diameter	7.0 mm
Generator temperature	80 °C	Outlet nozzle diameter	20.1 mm
Condenser temperature	30 °C	Total nozzle length	78.6 mm
Evaporator temperature	15 °C	Total ejector length	443.2 mm

The cooling circuit itself consists of a generator, which produces refrigerant vapor, connected to a separator, which then separates the vapor and potential liquid phase. The vapor flows into the ejector which serves as a key component, utilizing the energy of high-speed vapor to create a low pressure in the evaporator. The ejector is of axial design and its construction allows easy replacement for its sub-components. The cross-section of the used ejector is on the Fig. 2.

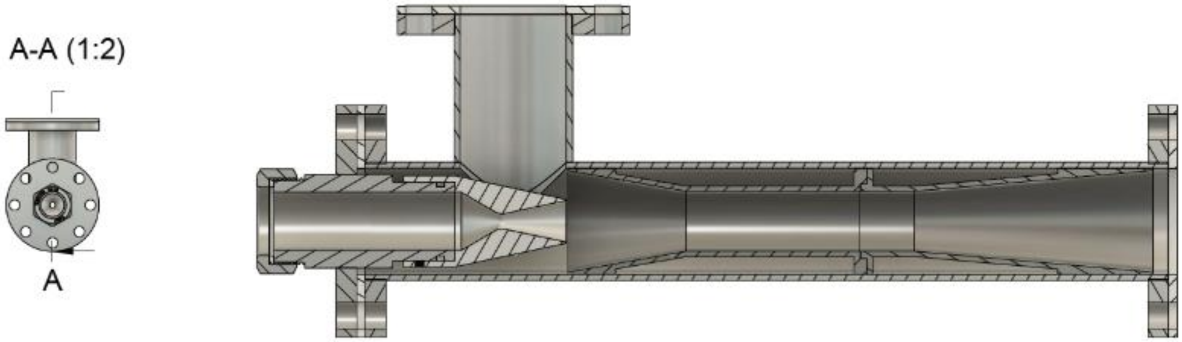

Figure 2: Cross-section of ejector

The condenser is attached to a liquid refrigerant receiver tank, which serves as a reservoir buffer and is made up of two smaller tanks with two discharge pipes, one connected to the separator, the other to the evaporator, effectively closing the cycle. The level of liquid in the tank is measured and this value serves as a trigger for the generator pump. This pump ensures the flow of refrigerant to the high-pressure part of the cooling circuit. On Fig. 1 is named as P_gen. Its type is 03 0333 by Barwig and construction is submersible with 20W DC motor. The pump is characterized by maximum flow parameters of 720 l/h and discharge pressure of 0.6 bar. Due to the significantly higher flow rate of the pump, it is necessary to operate it in on/off mode. The switch-on time was experimentally set to 90 seconds.

In the case of Fig. 1a, the evaporator is connected to the liquid tank via a simple valve, and the flow is regulated by pressure differences between the tank and the evaporator. This is the most standard setup of the ejector cooling cycle. In reality, no valve was used, but the pressure drop was achieved due to the relative vertical positioning of the evaporator and the liquid tank. In the second case according to Fig. 1b, the feeding of the evaporator is realized by a dosing pump of peristaltic type. This concept allows precise dosing of the refrigerant and at the same time it completely pressure separates the evaporator. Since the whole primary circuit is operated at very low pressures, the selection of such a pump is challenging. The generator, condenser and evaporator are all relatively simple plate type heat exchangers. The system was built with several measuring points, but the only measured variable in the primary circuit was the pressure, where the measurement of absolute values of pressure in the evaporator, condenser and generator parts were carried out. The positions of the pressure sensors were the same for both cooling circuit arrangements and are indicated in Fig. 1a.

All individual components are connected by piping with various technologies, where the ejector is connected by flanges for easy replacement for research purposes. The separator and generator are connected by threaded connection with gaskets, mostly due to compensation of thermal expansion. However, this type of connection is prone to infiltration, where air can seep into a pipe from the outside. All the other connections were carried out by pipe soldering. The overall design represents a compromise between ease of component replacement and system tightness.

Figure 3: Photo of ejector cooling system in the laboratories of the Institute of Energy Machinery

5. DESCRIPTION OF THE MEASURING TRACK

The ejector cooling system is a part of a larger measuring stand with heat source and cooling tower. The operating parameters of the ejector used exhibit a highly point-like character and the device reacts to their change by a sharp deterioration of the characteristics. Also, the reaction time of the ejector to a change in the parameters of the inletting vapour is very small. For these reasons, it was necessary to control the heat source appropriately. The heater consisted of an 18kW electric boiler. To achieve the smoothest possible output temperature, the power control was implemented in linear mode. A cooling tower was used to remove heat from the cooling circuit. This solution, due to the low temperatures achieved, has a significant positive effect on the cooling factor values of the ECS. However, at the same time, the cooling tower was also used as a consumer of generated cold. The overall schematic diagram of the measuring system is shown in Fig. 4.

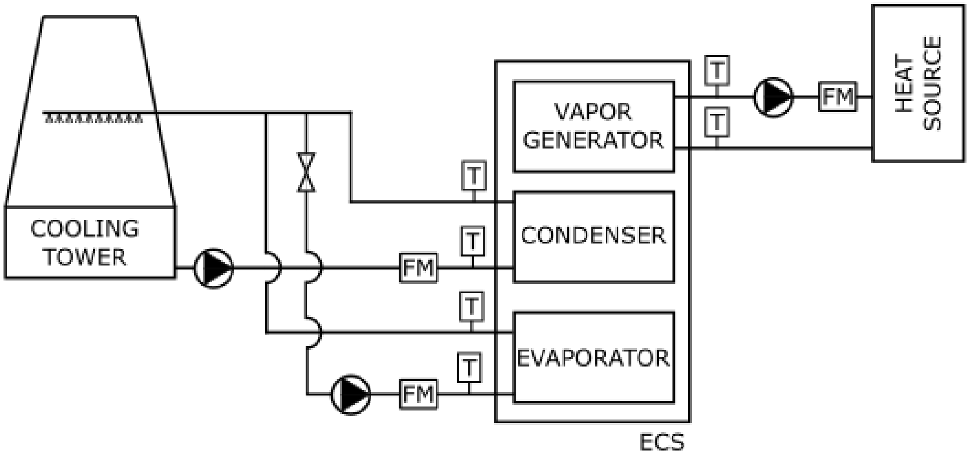

Figure 4: Schematic diagram of testing stand

The used working fluid between the heat source and generator was glycol, but for the circuit involving the cooling tower, water was used as the heat transfer medium. In contrast to the primary circuit, where only pressures were measured, in the secondary circuit temperature was measured on several locations as indicated on Fig. 3. Measurement of the fluid flows was carried out using three separate sensors in the secondary circuits of the evaporator, condenser, and the generator. From the measured data, the cooling power as same as others thermal powers where caltulated by standard calorimetric equation based on temperature change of seconrady working fluid. The EER was evaluated as ratio between cooling capacity and thermal power consumption of generator. The work of pump was neglected.

6. THE EXPERIMENT AND THE EVALUATION OF MEASURED DATA

The temperature conditions during the experiments were kept as close as possible to the design conditions. The average secondary temperatures were 88,54 °C, 21,98 °C and 20,98 °C for the generator, condenser and evaporator, respectively. The deviations for the individual experiments were minimal and in all cases less than 2,5 %. Fig. 7 shows the cooling performance progress of the tested machine in both configurations of refrigerant dosing to the evaporator. In both cases, the effect of the pump's operation that provides circulation through the generator (P_gen) is visible. The fluctuation in the cooling performance is due to the change in the operating conditions of the ejector, specifically the change in condensing pressure. This is directly affected by the height of the liquid refrigerant level in the tank. As already mentioned, the control of the generator pump is based on reaching a maximum level and therefore the change in level is accompanied by a change in cooling capacity.

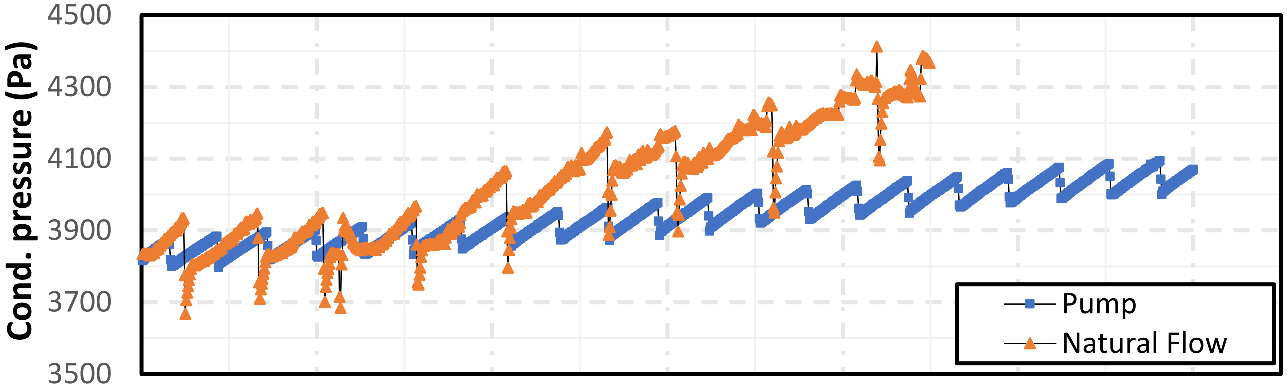

Figure 5: Time progress of the ECS's selected parameters during the experiments - Condenser pressure

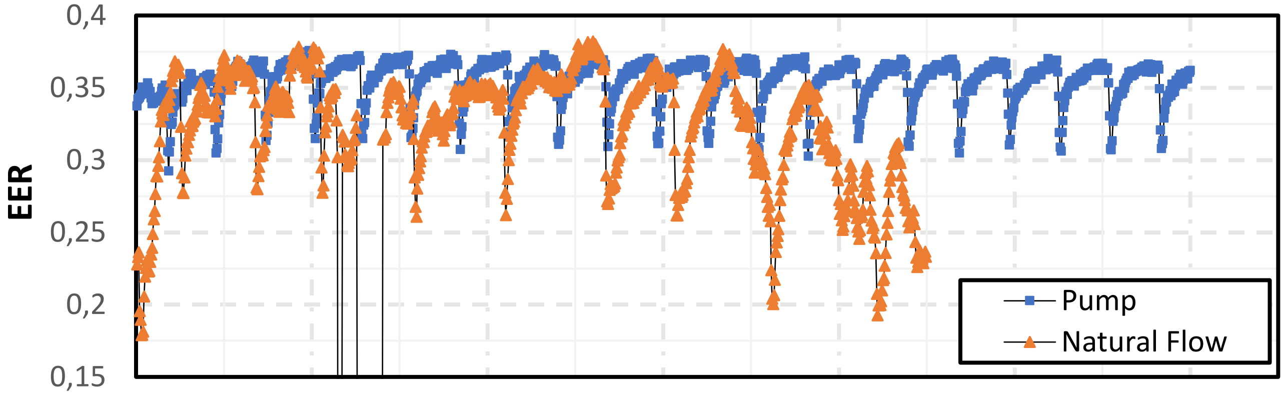

Figure 6: Time progress of the ECS's selected parameters during the experiments - EER

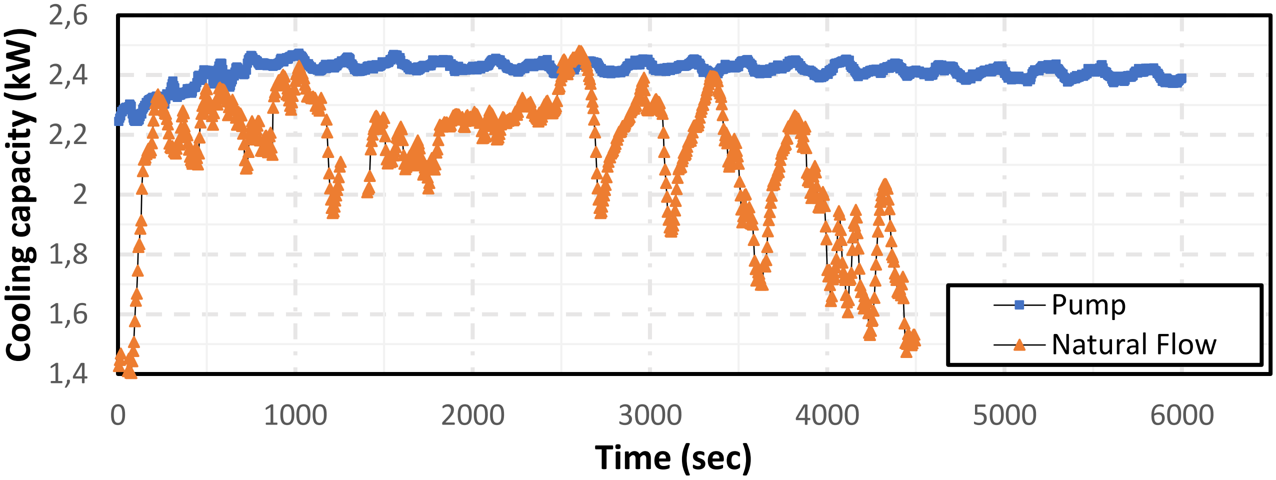

Figure 7: Time progress of the ECS's selected parameters during the experiments - Cooling capacity

From a comparison of the two waveforms it can be seen that in the case of refrigerant dosing to the evaporator by the pump, the cooling power's progress is noticeably smoother. The average obtained value is 2.38 kW with a standard deviation of 5.32 %. The operation of the chiller is also significantly more stable. This was due to the complete pressure separation of the evaporator from the liquid reciever tank by the peristaltic pump.

In the case of an evaporator filled by the pressure difference between the evaporating and condensing pressures, the average cooling power achieved has a value of 2.13 kW with a variance of 23.8 %. At the same time, a decreasing trend can be observed in this mode of operation. This can be clearly explained by the influence of machine inlet-leakages. This trend is observable in both cases, but is significantly steeper for flow by pressure differences only. The reason for the differences is the need for a marginally high level of refrigerant in the reservoir for the needs of sufficient evaporator flooding.

In the case of the EER (Energy Efficiency Ratio) parameter, the time course is similar as for the condensing pressure and cooling capacity. The waveform (Fig. 6) nature of the parameter's trend is evident, confirming the overal influence of the selected configuration, where the variant with natural flow showed and avarage value of 0.312 +- 7.36 %, and the variant with a evaporator pump 0.353 +- 1.50 %.

The most important results from the measurement is the stability of cooling power output, which was much more stable when the system was operated with the additional evaporator pump. For both operating configurations the condensing pressure is the key value and its evolution is shown in Fig.5. It is also possible to observe the effect of leakages of the machine during its operation. More significant changes are in the case of an evaporator directly connected to the liquid tank. One of the reason is that the volume above the refrigerant level in the tank is very small, so even a small air inlet causes high pressure changes.

7. CONCLUSIONS

The achieved cooling power of the machine is at comformity with the design 2.542 kW vs. 2.38 kW. In terms of deviation, the main change is the characteristics of the real ejector, which is burdened by the imperfections of the manufacturing proces and including all irreversibilities of the entire cycle. The sensitivity of the evaporator to pressure changes in the device, caused by intermittent operation of the generator pump, was experimentally determined. In these terms, the design of the refrigerant storage tank is important. It must have sufficient space in the area above the liquid level to minimise the effect of equipment leakage for a sufficiently long time. However, complete pressure separation of the evaporator from the liquid tank will ensure that optimum refrigeration performance is achieved. This knowledge is important for the design of the components of the refrigeration unit. In order to achieve optimum cooling performance and efficiency, it is important to ensure stable evaporator operation. The solutions can be based on either stabilization of the condensing pressure by continuous operation of the generator pump or complete pressure separation of the evaporator from the refrigerant receiver tank.

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