COOLING SYSTEM FOR HERMETIC COMPRESSOR BASED ON THE LOOP THERMOSYPHON

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Abstract

One of the simplest solutions to ensure the thermal control of a hermetic reciprocated refrigeration, or heat pumping compressor is related with the loop thermosyphon application. This paper presents experimental data obtained on two innovative loop thermosyphons - one with capillary structures and second without it. These thermosyphons are prime candidates for small hermetic compressor cooling solutions to replace typical oil-cooled and air-cooled systems, where commercially available heat exchangers cannot be used due to the high power and transport length limitations. The performance characteristics of two loop thermosyphons are discussed: (a) with vertical flat evaporator (one of its heat loaded wall has the sintered powder coating) and loop condenser, made from mini tube, sprayed by the cooling oil inside the compressor, and (b) horizontal mini tube evaporator embedded into the copper plate, two bendable transport lines and flat condenser (box) with fins on its outer surface. Air is the cooling media.

KEYWORDS

Cooling system, loop thermosyphon, hermetic compressor.

INTRODUCTION

When used for cooling and heating compressors, whether classified as positive displacement compressors or dynamic compressors, are used in air conditioning, refrigeration, and heat pump systems. As the key of these vapor compression system applications, the compressor raises the pressure of the working fluid so that it can be condensed to liquid at the heat sink temperature, expanded or throttled to reduce the pressure, and evaporated into vapor to absorb heat from the refrigerated source. In these systems, refrigeration compressors are a component in a closed loop system, which is tightly sealed (often hermetically) to prevent refrigerant loss. When used in air-conditioning, refrigeration, and heat pumps, they must be designed for a variety of refrigerants and compatible lubricants. Commonly used refrigerants include hydrochlorofluorocarbons such as R-22, or hydrofluorocarbons such as R-410A, R-407C, R-404A, and R-134a, or ammonia and various hydrocarbons. In the design of such compressors its thermal management is one of the most important components that determine overall performance and reliability. A proper understanding of heat transfer and the temperature distribution of various components in the compressor helps in determining the parts' geometry and materials selection. A small hermetic compressor usually is placed in the back of a refrigerator or air conditioner. R 134a and R600a are used as refrigerant. Typically the refrigerating capacity goes from 60 W to 350 W when these systems are operating at low evaporating temperatures (-20°C to -35°C). In the past the industrial application of loop thermosyphons was considered in details by Pioro L. S. and Pioro I. L., 1997 [1] and Rossi, L., Polasek, F., 1999 [2]. The original design of "Vapor-dynamic" horizontal thermosyphon which has a split vapor and liquid (coaxial) liners was suggested in 1985 by L. Vasiliev et al. [3]. Extended electronics applications of heat pipes and thermosyphons require transport of the dissipated thermal energy in horizontal orientation or horizontally oriented evaporator and condenser surfaces, and, typically, capillary structures in the evaporators for the heat transfer enhancement, Ptacnik J., Polasek F, 1999 [4]. The basic concepts related to the operation of vertical loop thermosyphons are well known and can be found, for example, in I. Rossi and F. Polasek (1999) [5]. The horizontal and vertical thermosyphons alternatives were considered in 1994 by L.L. Vasiliev [6]. Chu et al. (1999) [7] presented original test data for a traditional-design loop thermosyphons with flat vertically oriented evaporators. Garner and Patel (2001) [8] outlined in detail a number of electronics applications where use of loop thermosyphons would be technically and commercially appropriate. However, some further improvements and technical innovations are needed for a variety of loop thermosyphons to possibly become accepted as a standard by refrigeration and heat pumping industry.

Generally in the loop thermosyphon the heat transfer is considered to be affected by many factors, such as type of the working fluid, quantity of the working fluid, pipe diameter, pipe length, and ratio of cooled surface to heated surface, adiabatic length between heated and cooled sections, heat flux and operating temperature. The evaporator and condenser of the loop thermosyphon can be made of carbon-steel, cupper, or aluminum. Propane, R 134a, R 600, or ammonia can be used as working fluid. When the copper is allowed to be applied water is the best working fluid. From the experimental data a reasonable filling ratio of working fluid and heat transfer coefficients for evaporator and condenser sections need to be obtained. In order to establish heat transfer correlations for the application in the design program for the loop thermosyphon heat exchanger, regression analysis could be applied to experimental data for heat transfer coefficients in evaporator and condenser. The review on heat pipe and thermosyphon heat exchangers was published by L.L.Vasiliev in 2005 [6]. There are many different types of thermally driven two-phase loops. They can be used in devices for the heat transfer like pumpless loop thermosyphons or Two Phase Loops (TPL) [7], which are working in a steady-state mode or in a periodic state if are gravity or antigravity assisted [8], in devices like as Pulsating Heat Pipes (PHP) and lastly in devices for the mass transfer like bubble pumps (BP), experimentally investigated by using different fluids in connection with the development of non-compression refrigeration systems. The application of miniature heat pipes and thermosyphons heat exchangers for compressor cooling was mentioned in [9]. In the loop thermosyphon, various types of flow instabilities occur depending on the system geometry, the working fluid filling ratios and the operating conditions, and often lead to abnormal behavior such as limit cycle oscillations or premature dry-out. Due to the coupling between momentum and energy transport the theoretical analysis of the loop performance is very complicate; therefore it is necessary that these problems be solved experimentally. There are several physical mechanisms restricting the "low-thermal-resistance" transport of the thermal energy from the evaporator to the condenser of the loop thermosyphon: (a) fluid circulation limitation, (b) capillary limitation in the evaporator, and (c) critical heat flux limitation in the capillary structure of the evaporator. The main thermal characteristics of the thermosyphon are the maximum capacity, the heat flux in the evaporation zone and thermal resistance. For the characteristic temperature one can use the temperature of the evaporator wall or the vapor. The thermal resistance of thermosyphon is usually written as:

$$R = \frac{T_e - T_c}{Q}, \qquad (1)$$

where T_e and T_c are the mean wall temperatures of the evaporator and the condenser respectively, and Q is the heat flow transferred from the evaporator to the condenser. It is also necessary to know the temperature of the condenser wall.

1 EXPERIMENTAL SET-UP

The experiments with developed loop thermosyphons was carried out on the experimental set-up (Fig.1), which represented the heat pump with the demountable compressor. This set-up was performed to reproduce the mode of the device applications close to realistic.

Figure 1. Experimental set-up for the compressor cooling system testing

1.1 Loop thermosyphon (LTS) with sintered powder wick on the flat evaporator heat loaded wall

The photo of the thermosyphon is shown on Fig.2.

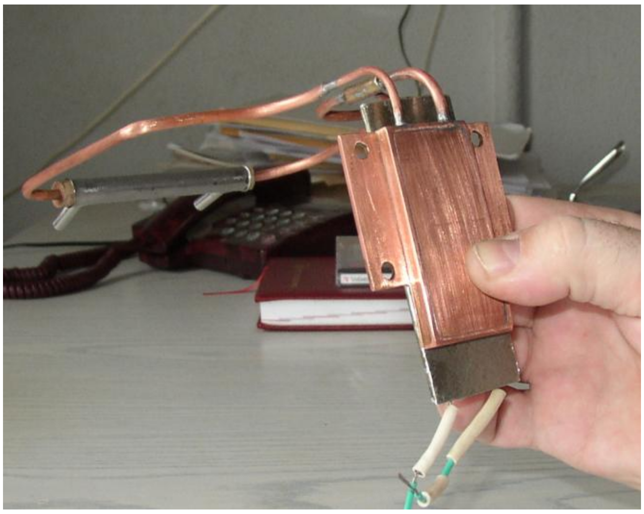


Figure 2. Experimental loop thermosyphon with the electrical heater (on the evaporator) and the liquid heat exchanger on the condenser part

To determine the characteristics of LTS, the indoor tests consist of LTS, plate electric heater, voltage regulator, power supply, liquid heat exchanger (tube in tube) and data acquisition. The schematic diagrams of the experimental set-up is shown on Fig. 3. The loop LTS is made from a copper and has a flat evaporator with a thin layer (0.3 mm) of the copper sintered powder wick on the one of its inner surface. LTS evaporator and condenser were connected to each other by two small diameter (2mm) bendable tubes (one for vapor and second for liquid), Fig.2. The evaporator is contacted with the heat-loaded cylinder head of the compressor. Such type of porous coating ensures the heat transfer enhancement up to 5 times to compare with the plain tube thermosyphon. A vacuum pump was used to remove air from the inner space of the thermosyphon. No thermal insulation was used on the heater block to closely simulate the real operational conditions. The flat evaporator (Fig.2) has a good thermal contact with a cylinder head of compressor, the condenser is cooled by the oil circulation inside the compressor shall. In the preliminary experiments the electric heater was used instead of the compressor cylinder head to calibrate the heat load of LTS. The flat thermal insulating block pressed the electric cartridge heater to the evaporator and a central hole for the thermocouple measuring the heated wall temperature.

The general aim of this experiment was to estimate the possibilities of the internal oil circulating cooling technology to reduce the temperature of the cylinder head :

- Determine the temperature distribution along the device for different heat loads;
- Estimate the device maximum heat transport capacity;
- Evaluate the dependency between the device thermal resistance and the rate of heat dissipation.

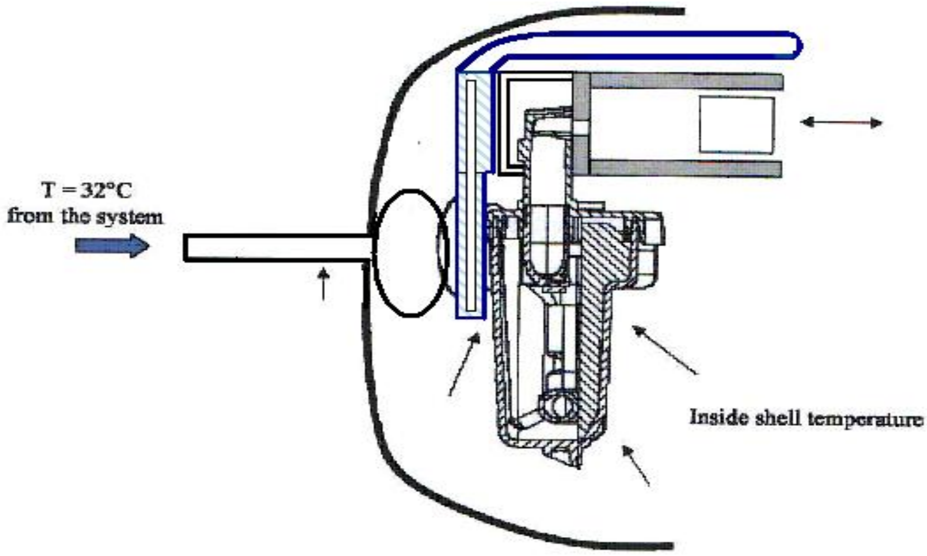


Figure 3. Compressor body cross with LTS (blue color)
as a cooler for the cylinder head.

The test data in terms of the characteristic temperatures of the copper block and LTS components are shown in Figs. 4, where the temperatures are plotted versus the time. To evacuate and fill-charge working fluid of the LTS, the three-way valve was installed. A kind of filling working fluid was water, ethanol (C2H5OH) and binary mixture of water and ethanol. The heat load was turned on from zero to the nominal level. The LTS started to work without a temperature overshoot typical for conventional thermosyphons. The temperatures of the heater block stabilized within five minutes after the heat load was turned on. During the calibrating tests the multi-rings (cylindrical coil) condenser was cooled by the water in the liquid heat exchanger. During the tests of LTS inside the compressor the oil spraying technology was used. The oil spraying cooling is not optimal and efficient and needs to be further redesigned to improve the intensity of condenser cooling. The calculation for the heat transfer between the condenser and the lubricating oil of the compressor is complex since the oil is circulated for lubrication purposes.

The flat copper evaporator with the footprint of 50 mm by 80 mm had a sintered copper capillary structure on the one inner surface that was 0.3 mm thick with the effective pore radius of about 50 μm. The heat transfer coefficient in the porous structure of the evaporator was 30 000 W/m^{2}K, [9]. The thermal resistance of this thermosyphon was R = 0.03 K/W. Unfortunately the condenser cooling by the oil spray was not sufficient and limited the overall heat transfer rate through the thermosyphon, Fig.4.

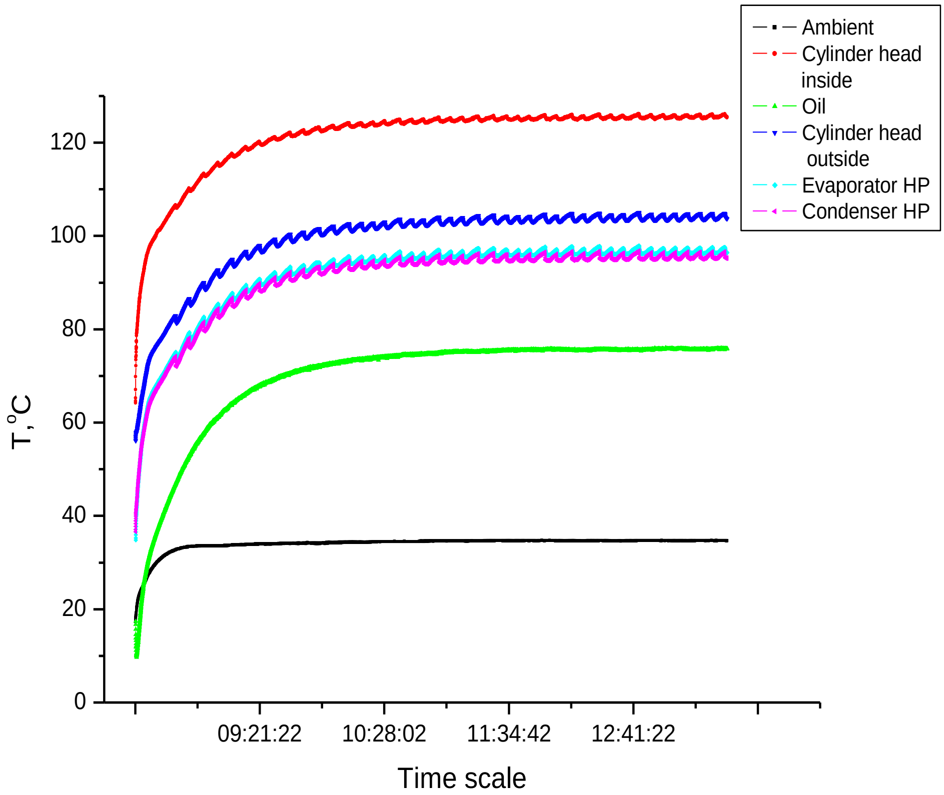


Figure 4. Temperature evolution in the cylinder head, thermosyphon evaporator, thermosyphon condenser, evaporator of the cooling machine, gas in the sacking line of the compressor as a function of time

The experimental LTS after the preliminary tests was put in the compressor and all the necessary temperature measurements were performed. Fig. 4 shows us the temperature evolution on the cylinder head (inside and outside), thermosyphon evaporator, thermosyphon condenser, oil and ambient. The temperature difference between the evaporator wall and condenser wall was less than 1 ^{0}C. It means that the temperature drop and heat transfer resistance between the oil and the LTS is mach more.

When we analyze the temperature difference between the thermosyphon evaporator and condenser and compare this difference with the temperature difference between the condenser and the oil, we can conclude, that the heat transfer intensity inside the thermosyphon is at least 100 times more., Fig.4. This is due to the low heat transfer between the condenser surface and the oil sprays. If the oil spray cooling technology will be improved the thermosyphon cooler could be considered as a good solution to improve the compressor thermal efficiency. The alternative is to use the additional heat exchanger between the thermosyphon condenser and the air outside the compressor.

1.2 Pulsating loop thermosyphon (PLT) as a compressor cylinder head cooler

The experiments with above mentioned loop thermosyphon testify that more efficient mean of compressor cooling is direct contact of the thermosyphon condenser with additional air heat exchanger (instead of the oil cooling inside the compressor), installed above the compressor shell. For such a case there is a possibility to use less expensive pulsating loop thermosyphon (PLT). The evaporator of thermosyphon is made from the capillary pipe embedded into the copper plate, Fig.5. The plate is contacting with the cylinder head.

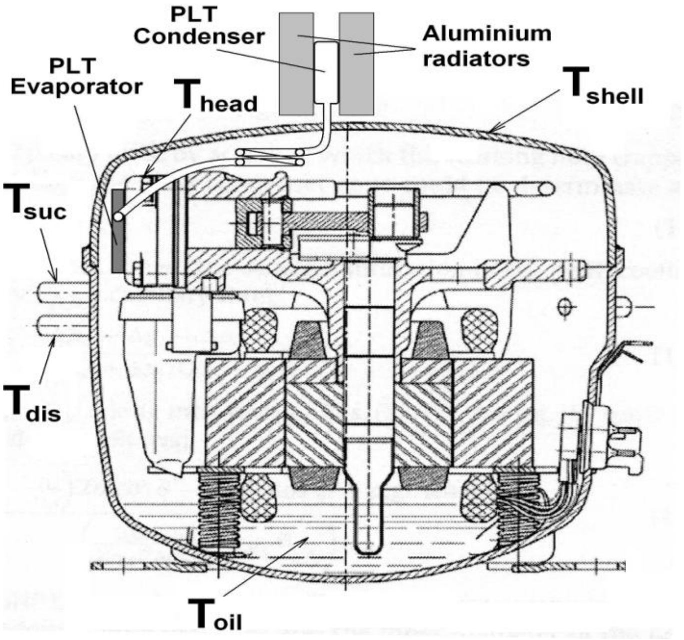


Figure 5. Cross section of compressor with pulsating loop thermosyphon (PLT)

The design and parameters of PLT are described in [10-11]. Such PLT is made from the copper U- tube with the condenser box disposed on the upper part of vertical PLT, Fig. 6, 7.

Figure 6. PLT evaporator and transport zone with two pipes
for vapor and liquid transport between the evaporator and condenser

Two coils of vapor and liquid lines (as vibration isolator), Fig.6, prevents the PLT from destruction during the compressor vibrations. R-22 as the working fluid for the preliminary PLT tests was chosen. The thermophysical and thermodynamic properties of R-22 are close to propane and propylene – vacant fluids for PLT. The schematic of the PLT and its photo is shown on Fig.7. The vapor and liquid lines are connecting the evaporator (inside the compressor) and the condenser box disposed outside the compressor. The compressor box is in good thermal contact with aluminum-finned plates, just forming the heat exchanger, Fig. 5, 8.

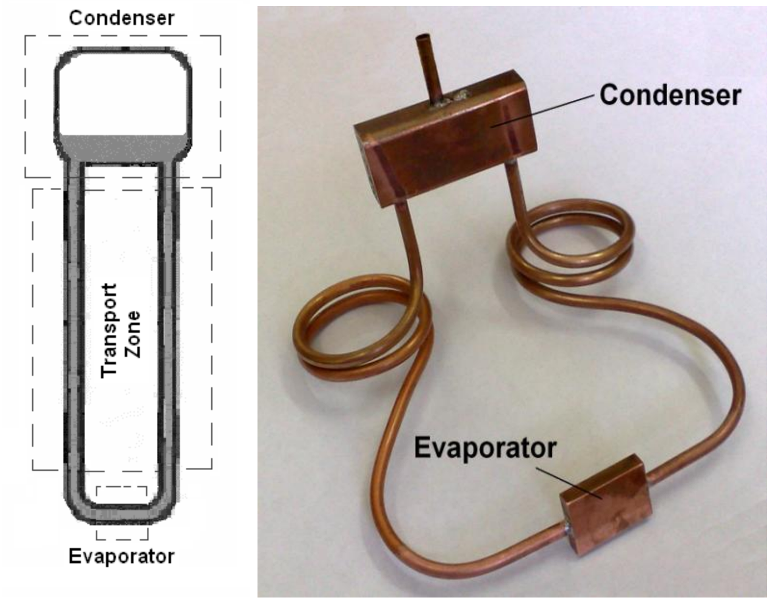
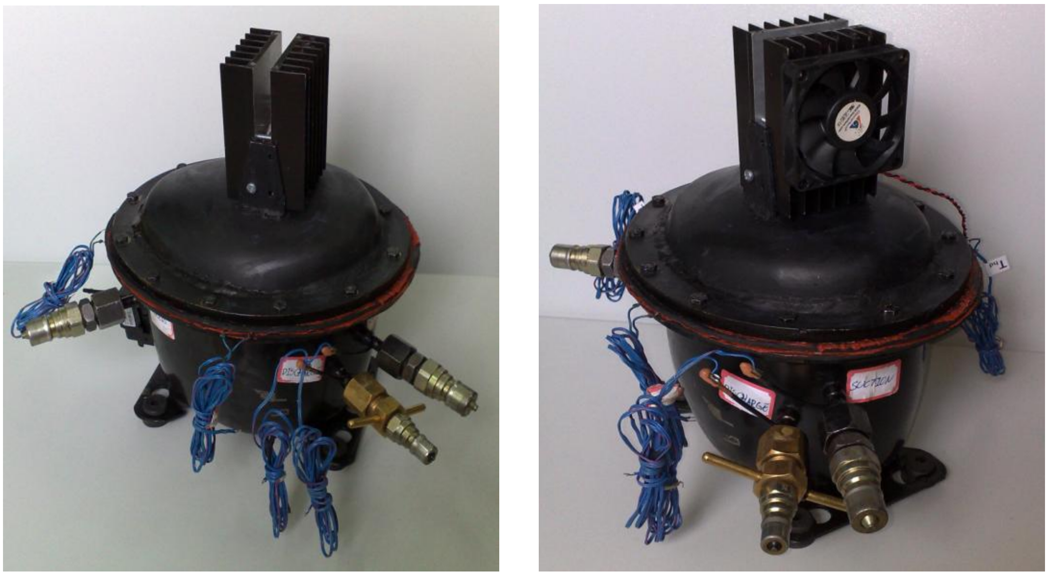


Figure 7. Scheme and photo of PLT for the compressor cylinder head cooling

Two different tests of PLT as the cylinder head cooler were done. The first set of tests was realized using PLT cooled by natural convection of air (no fan), Fig.8a. The second set of experiments was devoted to the heat transfer enhancement between the PLT condenser and the ambient using the forced convection cooling technology, Fig.8b.



a) b)

Figure 8. Photo of compressor with PLT:
a – free convection cooling, b – cooling with fan

The PLT condenser consisted of the flat copper box with the footprint of 48 mm by 12 mm and 25 height without any capillary structure inside, connected with the evaporator by two bendable tubes. The smooth-wall transport lines were 2x38 cm long. The PLT was filled with 6.5 cm^3 of the working fluid. Thermocouples were pressed into small diameter holes in the aluminum plates of the condenser. Thermocouples also were located in the middle of the vapor and liquid line of PLT. The test data are shown on Tables 1-2. Thermocouple number 6 was located on the top portion of the far end of the condenser.

The tests of the compressor were performed with such parameters:
ambient temperature – 26 °C;
gas outlet pressure – 23 bar;
gas sucking pressure –1,5 bar;

An Agilent 34970A data acquisition system was used to record all temperature measurements. This device has a resolution of 0.02 °C. The data acquisition unit and T-type thermocouples were compared to a precision digital resistance temperature device with a rated accuracy of 0.03 °C. The system accuracy was found to be within 0.2 °C over the range being studied. In the steady state, the readings of the thermocouples fluctuate within 0.2 °C. The uncertainty of the electrical power through the power analyzer amounts to 0.5% of the reading.

The temperature measurements were made as:
$\mathbf{T_{head}}$ – cylinder head;
$\mathbf{T_{shell}}$ – compressor shell;
$\mathbf{T_{oil}}$ – oil;
$\mathbf{T_{dis}}$ – gas temperature at the compressor exit;
$\mathbf{T_{suc}}$ – gas temperature at the compressor entrance;
$\mathbf{T_{con}}$ – PLT condenser entrance;
$\mathbf{T_{evp}}$ – PLT evaporator entrance;
$\mathbf{Q_{refr}}$ – heat flow at PLT evaporator (cooling rate);

The experimental data were obtained for three different cases: traditional compressor cooling system, compressor cooling system with PLT (natural convection in the heat exchanger) and compressor cooling system with PLT and forced convection cooling of the heat exchanger. The summarized experimental data are recollected in the Tables 1-2.

During the experiment we can see on the monitor screen the data collected in the tables or the graphics, the temperature field at a given time or the dynamic of the temperature field change in time. The heat load Q of the PLT is determined by the computer program depending on the heater electric resistance. Q_{max} is determined as follows. For a fixed PLT orientation in space the electric heater is switched on. After some time the temperature field along a PLT becomes stationary and is recorded in the file. Then the PLT heat load is increasing by the step ΔQ and the temperature field along PLT is fixed once more. The Q_{max} is fixed when there is a non proportional dependency between the temperature change (thermocouples data disposed below the electric heater) and the heat load change. In this case we testify a sharp increasing of the temperature. For the precise measurements of this PLT crisis value we use a small step of the heat load ΔQ.

Table 1. The experimental data of the temperature distribution inside the compressor for three different modes of compressor cooling and three values of the cooling power

	T_{head}, °C	T_{shell}, °C	T_{oil}, °C	T_{dis}, °C	T_{suc}, °C	T_{cond}, °C	T_{evp}, °C	Q_{refr}, W
Without cooling	**143.2**	**76.5**	**93.1**	**128.0**	**26.1**	**63.3**	**-7.9**	**136**
With PLT	**119.5**	**75.2**	**89.5**	**117.6**	**26.0**	**60.1**	**-7.8**	**138**

cooling								
PLT with Fan	**110.3**	**72.4**	**85.9**	**112.6**	**26.3**	**59.9**	**-8.1**	**137**

Table 2. The temperature difference between the key parts of the compressor working without PLT and with PLT cooler

	ΔT_{head}, °C	**ΔT_{shell}, °C**	**ΔT_{oil}, °C**	**ΔT_{dis}, °C**
With PLT cooling	**–23,7**	**–1,3**	**–3,6**	**–10,4**
PLT with Fan	**–32,9**	**–4,1**	**–7,2**	**-15,4**

Following the data of the Table 1-2 it is interesting to apply the PLT cooler with fan to reduce the temperature of the cylinder heat down to 30 ^{0}C to compare with the traditional compressor oil cooling system. The results of this study could be applied to actual compressor design in industry and have resulted in improved compressor performance.

CONCLUSION

1.The heat transfer analysis aimed to predicting and experimentally check mean temperature of the principal heat loaded components of hermetic reciprocating refrigeration compressor was performed to decrease the temperature of the refrigerant and increase its density in the compressor piston.
2. Two loop thermosyphons, as a two-phase cooler was considered as the alternative to solve this problem.
3. The Loop Thermosyphon with porous coating of the evaporator (LTS) ensures the heat transfer enhancement up to 5 times to compare with the plain tube thermosyphon and started to work without a temperature overshoot typical for conventional thermosyphons.
4. The heat transfer coefficient in the porous structure of the LTS evaporator was 30000 W/m^2 K. The thermal resistance of this thermosyphon was R = 0.03 K/W.
5. As an option to the **l**oop thermosyphon (LTS) an advanced pulsating loop thermosyphon (PLT) was developed. This PLT was investigated on the experimental set-up and demonstrated the cylinder head temperature drop above 30 ^{0}C to compare with the traditional oil cooling.

References

1. Pioro L.S., Pioro I.L., Industrial Two-phase Thermosyphons, Begell House Inc. 1997.
2. Rossi, L.and Polasek, F., "Thermal Control of Electronic Equipment by Heat Pipes and Two-Phase Thermosyphons." Proc. 11th International Heat Pipe Conference, September 1999, Tokyo, Japan, Keynote lecture, pp. 50-74.
3. Vasiliev L.L. et al. "Heat transfer Device" US Patent No. 4.554.966, Nov. 26, 1985
4. Ptacnik J., Polasek F., Present state of heat pipe technology in the Countries of Mutual Economic Assistance", Proc. 3rd International Heat Pipe Symposium-Tsukuba, 12-14 September, 1988. Ed. by Y. Kobayashi, Kanji Negishi, K. Oshima, pp. 13-30.

5. Garner, S., and Patel, C., "Loop Thermosyphons and their Applications to High Density Electronics Cooling", Proc. of IPACK'01 The Pacific Rim/ASME International Electronic Packaging Technical Conference and Exhibition, July 8 - 13, 2001, Kauai, Hawaii. IPACK2001-15782
6. Vasiliev L.L., Heat pipe technology in CIS Countries, Proc. of the 4th International Heat Pipe Symposium-Tsukuba, 16-18 May, 1994. Ed. by Y. Kobayashi and K. Oshina, pp.12-24
7. Chu, R., Simons, R., and Chrysler, G., "Experimental Investigation of an Enhanced Thermosyphon Heat Loop for Cooling of a High Performance Electronics Module," Proc. Of the 15th IEEE SEMI-THERM Symposium, 1999
8. Vasiliev L.L., Heat Pipes in Modern Heat Exchangers, 2005, Applied Thermal Engineering, 25, 1-19
9. Possamai F.C., Setter I., Vasiliev L.L. "Miniature heat pipe as compressor cooling devices", Applied Thermal Engineering 29 (2009) 3218-3223
10. Konev S., Aliakhnovich V., "Investigation of Oscillating Heat & Mass Transfer in Capillary Heat Pipe", 13th Intern. Heat Pipe Conf., September 21-25, 2004, Shanghai, China.
11. Konev S.V. , Aliakhnovich V., "Heat transfer device for microelectronic cooling", MIF-VI, May 19-23, 2008, Minsk, Belarus (in russian).