COMPARATIVE PERFORMANCE OF WORKING FLUIDS IN LOW-TEMPERATURE VAPOR-TURBINE CYCLE

Dr. Sc., M.Yu. Boyarsky[1], PhD, A.I. Nikolski[1],
MsD, M.B. Sapozhnikov[1], PhD, A.A. Shipkov[1]

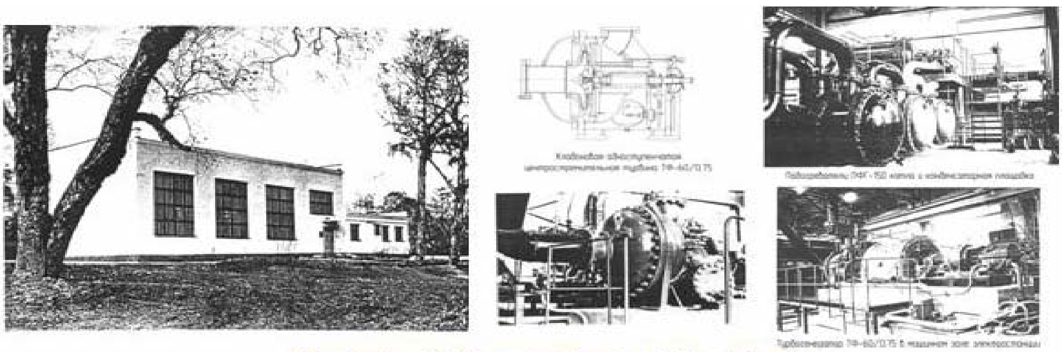
[1] "Nauka" SC, 9/1 Krasnokazarmennaya St., Moscow, Russia
Tel/fax: (095) 918-19-86 e-mail: nauka@geotherm.ru www.naukasc.ru

KEY WORDS

Turbine, working fluid, plant, performance

1. INTRODUCTION

Using of Low temperature Cycles (LTC) is important in various applications of the modern power generation technology. Geothermal technology, wasting heat use, stations operating with renewable and solar sources of energy are based on LTC. In these applications heat source temperature is in a range of 100…150 C and sink temperature is close to ambient from 40 C down to 15 C. LTC of different configurations could be also integrated with traditional power generation cycles. This may give some benefits in the enhancing efficiency of power generation and optimal station design.
The world-first geothermal power station (GPS) operated with Freon R-12 [1]. The station was a basic part of the Paratunskiy Power Plant, which was built in 1965-1967 [2] in the USSR at Kamchatka Region. Gross Power of GPS in Russia was 700 kW in 1967. Technical parameters and general view of the plant are presented in Figure 1.



Technical Characteristic of the Station:

Working Fluid (WF)	R-12
Power Supply to the Customers	500 kW
Generator Power	720 kW
Water Inlet Temperature	90°C
Heating Water Flow Rate	200 m³\hr
Cooling Water Temperature	5°C
Cooling Water Flow Rate	1500 m³\hr
R-12 Pressure at the Turbine Inlet	14 at.
R-12 Pressure at the Turbine Outlet	5 at.
Internal Power Efficiency of the Turbine	0,8

Fig. 1. General View (left), Turbo-generator and Technical Characteristic of Paratunskaya GeoPP

Retrospective in practical applications during more then 30 years shows a great variety in selecting of a working fluid (WF) for LTC. Different types of working fluids presented in Figure 2 have been used in the world – wide developments since 1965.

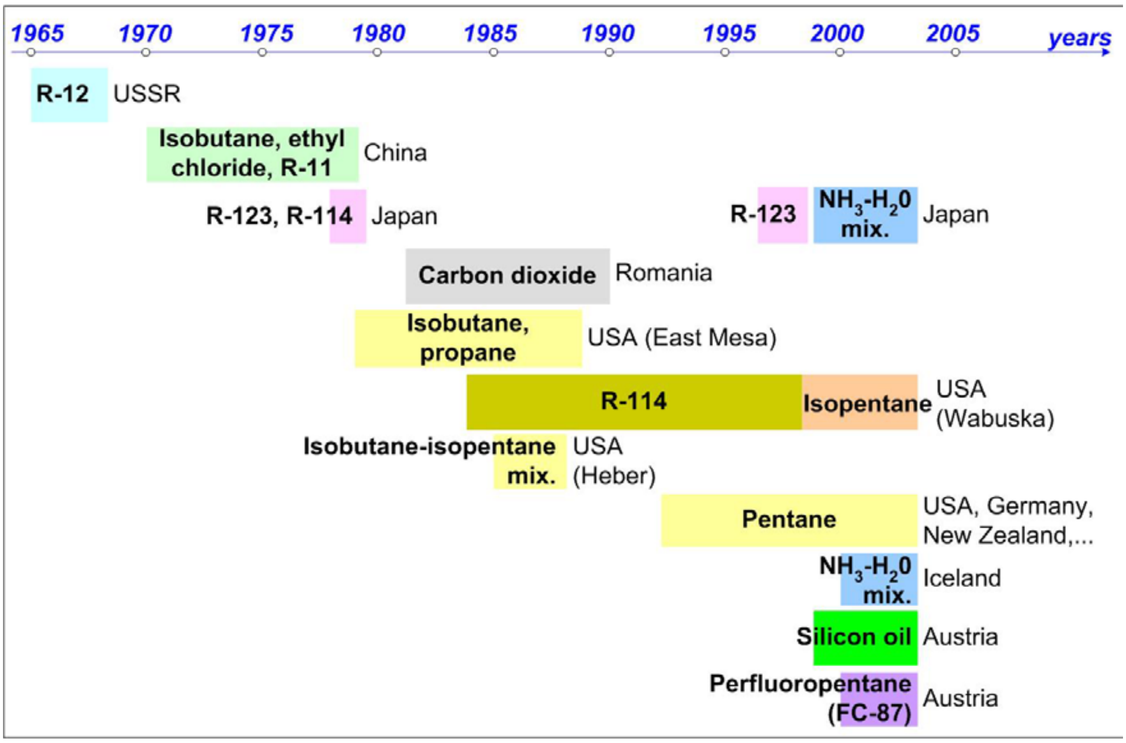


Fig.2. Practical applications of a working fluid (WF) for LTC.

A group of "pure" working fluids (WF) includes both flammable hydrocarbons (HC): Butane, Pentane, and their derivatives - nonflammable HCFC like R-12 and R-11 (CFC), R-123 (HCFC). Industrial plants operated with carbon dioxide were tested in the ORADEA University (Romania). Fluorocarbon refrigerant (FC) is used in the Althem GPS, Austria.

Multi-component mixtures – mixed working fluids (MWF) was proven to be efficient in geothermal technology. Prof. L.M. Rozenfeld studied application of Water-Ammonia mixture in 1955 [3] and pointed out its potential efficiency. Kalina (USA) further developed this idea [4]. Geothermal power plant in Iceland built in 1999-2001 is based on the Kalina cycle [5]. MWF – a mixture of i-Butane and i- Pentane is used in the Herber power plant, San-Diego-USA [6].

Power generation technology is still not mature but developing extensively. Historically, power stations based on these type of cycles are also called Binary Power Stations. LTC is frequently named as Organic Rankine Cycle [7]. Binary Power Plants developments include the LTC use. Further in this paper, we use a term LTC, which seems to be more general and could cover potential variations in the cycle configurations in different applications.

Initial applications of LTC were not always successful. However, practical issues and difficulties were basically related to a lack of experience in engineering and equipment design. Meanwhile, application of LTC is growing up in various fields. Nowadays, GPS with LTC for the Verkhne-Muntovski Plant is planning for 4 MW of power production [8].

In USA, a pioneer GPS in San Diego, which was started in 1980 produced only 5 MW of 45 MW as planed. In 1993 the second plant consisting of six modules of 40 MW went into commercial operation producing 113% of its rated net output [6].

The Altheim Project, Austria is based on a local GPS of a total power of 1000 kW and also provides heating for a local community. Thanks to its efficient operation, a significant reduction of air pollution is also provided [9].

These and other successful applications of LTC are based on an optimal system design of each component in a chain, which includes: source of heat supply, LTC configuration and working fluid, power station equipment, plant modular structure, operational maintenance. Selecting or designing a WF based on modern environmental requirements is one step in the chain, which could influence essentially on the other constituents in this chain.

A goal of this paper is analyzing of the WF properties and reciprocal influence between WF and LTC that could help to enhance the efficiency in GPS developments.

2. RECIPROCAL INFLUENCE OF LTC AND WF

A type of heat source, LTC configuration and working fluid properties are among of the most important factors that should be jointly analyzed at very first steps of a development. This is due to their essential reciprocal influence. It can be seen from the analysis of the Unit-IV of the Verkhne-Mutnovski GPS [8]. The Binary station is based on a cycle, which consists of two combined circuits operating with different WF [10]. The high temperature circuit is based on Rankin cycle and operates with Water from the geothermal drill hole. It also provides heating to the second circuit – LTC at evaporator temperature of 90 C. The LTC could operate with different WF. Schematic of this typical Binary Power Station is presented in Figure 3.

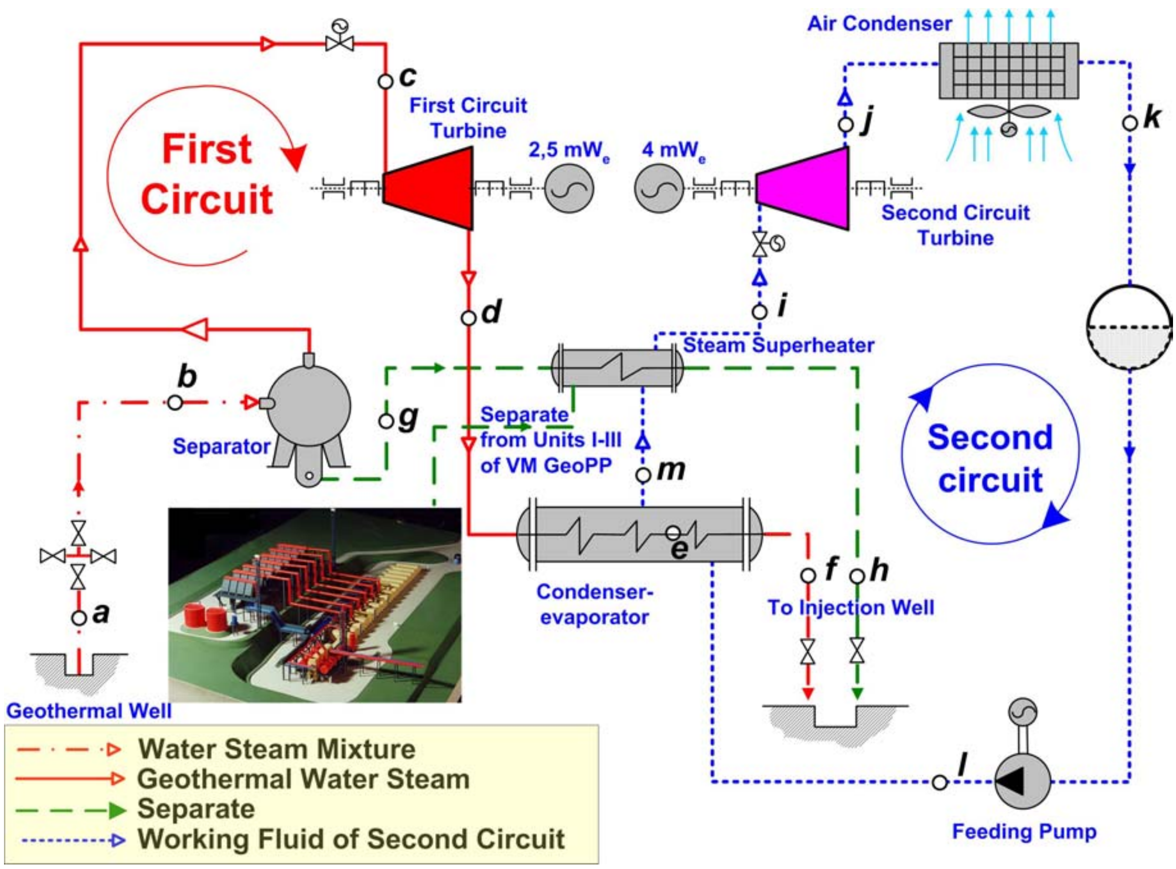


Fig.3. Principal heat scheme of VM GeoPP unit IV

In general case a heat supply to LTC includes three steps. Step 1 includes preheating of the WF up to evaporating temperature. Step 2 is a WF steam generation at T = const. Step 3, which may be optional, is connected to a vapor superheat for potential enhancing the cycle efficiency. A simplified process is presented in temperature-entropy (T-S) diagram, Figure 4.

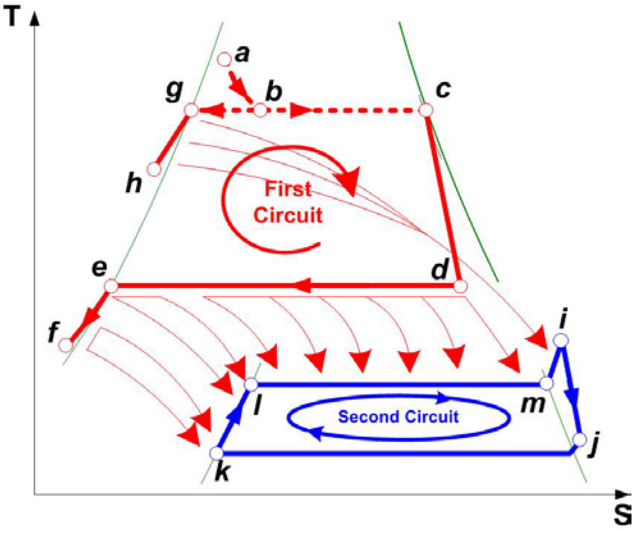


Fig. 4. Scheme of combined cycle in graph T-s.

Nine pure WF of different nature and thermodynamic properties have been tested with a LTC cycle model. The model allows evaluations of a Thermal Coefficient of Performance η_T with different vapor superheat $\Delta T_{S\text{-}H}$. Based on the results presented in Figure 5 all the tested WF can be divided into two groups.

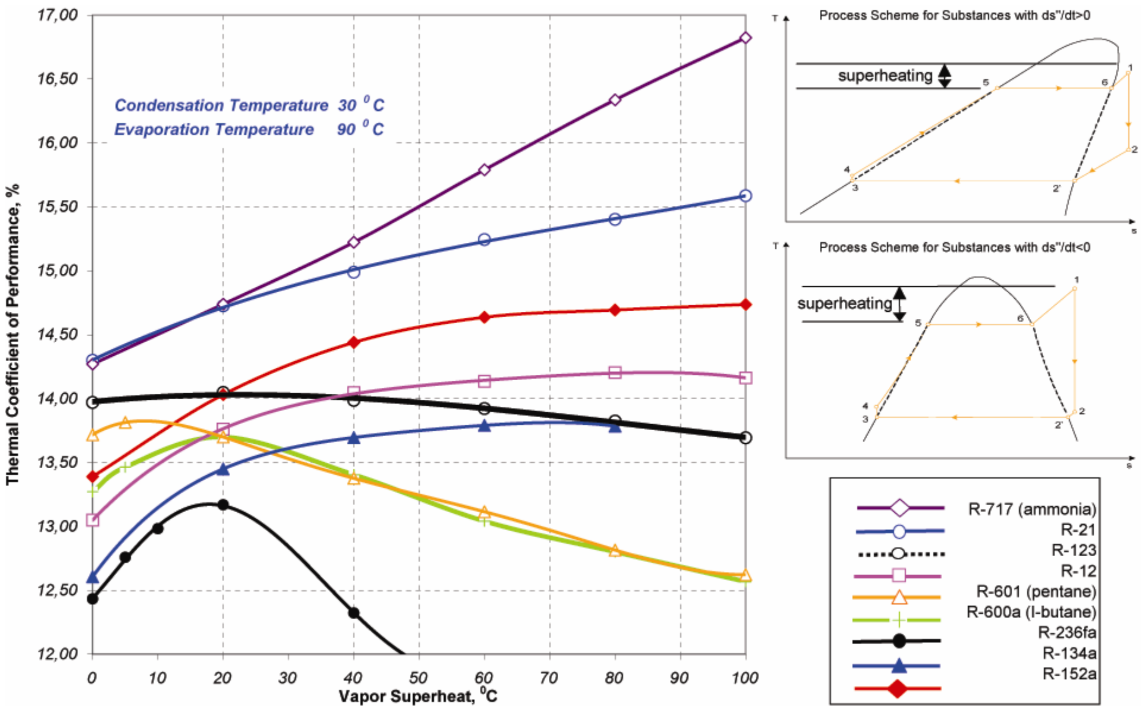


Fig.5. Effect of steam superheating upstream of turbine upon heat economy.

Group 1 consists of Ammonia (NH_3); HCFC: R-21, R-152a; CFC: R-12 and HFC: R-134a. For these substances $\Delta T_{S\text{-}H}$ increase improves the efficiency.
Group 2 includes CHFC R-123, HFC 236fa, R-600a (i-Butane) and R-601 (Pentane). In this group, superheating of vapor initially improves the efficiency. However, further increase in $\Delta T_{S\text{-}H}$ leads to negative results. An extreme point of the function $\eta_T = f(\Delta T_{S\text{-}H})$ depends on the WF properties.
It was noticed that substances in Group 1 and 2 have different slope (dS" / dT) of the right-side boundary line in vapor-liquid region. For Group 1(dS" / dT) is negative. On the contrary, for Group 2 it is positive.
For Group 2 behavior of the function $\eta_T = f(\Delta T_{S\text{-}H})$ may be explained taking into account the following considerations. Vapor superheat increasing causes increase in average temperature for both the heat source and heat sink. It is known that sink temperature influence on the η_T greater than heating temperature. An appropriate data supporting this statement is presented in Figure 6.
This illustrate the interconnection of the optimal cycle configuration with and without of heat exchanger for WF superheating and its properties. An optimal heating temperature to provide a maximal η_T is also different for different WF.

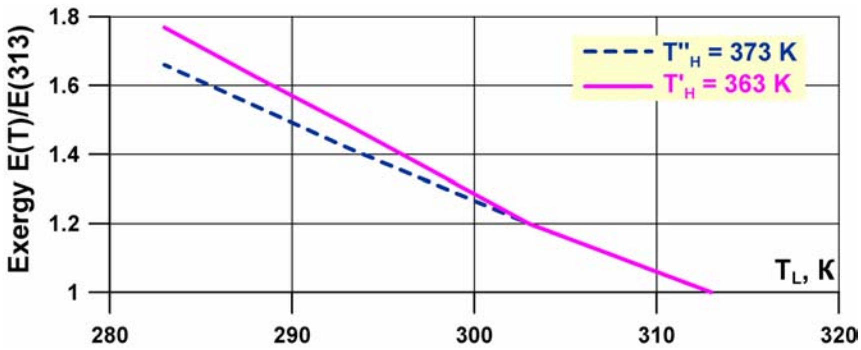


Fig. 6. Sink temperature influence on the exergy of the heat source.

3. MODERN REQUIREMENTS TO WORKING FLUIDS

There are many variables to consider in selecting or designing a working fluid. We focus on both characteristics general that include toxicity, flammability and environmental characteristics and specific – those related to the efficiency of performance LTC with WF.
A. General requirements obey to standard rules and regulations developed either internationally or in the country. After signing the Montreal Protocol a lot of research and developments have been devoted to finding CFC substitutes for R-12, R-11, R-114 that have been used widely in refrigeration and heat pumping technologies. In geothermal technology LTC should operate at the temperature range identical to those, which is typical for heat pumps. Experience accumulated at the last decade of nineties is useful for LTC developments. Information of prime interest related to basic thermodynamic properties of refrigerants and their general characteristics is presented in **[**11**],** by J.Calm . This information is also available from [12].
Flammability characteristics are of traditional prime concern. A lower flammability level (LFL, volume % in the air) signifies the case fractionation may become flammable.
Toxicity could be rated with TLV – Threshold Limit Value on a time-weighted average measured in PPM. Value of TLV > 400 ppm signifies nontoxic refrigerants.
Environmental characteristics could be presented by two basic parameters Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) for 100 years of integration. Public relations

to these criteria is not stabilized yet. Most of the countries have signed the Montreal Protocol whereas the Kyoto Protocol is under debating.
Although there are exist other important characteristics the selected parameters: LFL, TLV, ODP and GWP could initially characterize working fluids to be selected for further analysis. It is not simple task to develop a WF or refrigerant, which matches all the general requirements. In practical applications a reasonable level of compromise contradicting parameters should be found out.
B. Specific Requirements are related to the LTC performance. They could be evaluated with different criteria and objective functions specified for a development.
A coefficient of performance (COP) commonly presenting a ratio of product and consuming recourses is a widely used characteristic. Applied to evaluating LTC efficiency it could be structured in different ways.
In power engineering, one of traditional criteria is presented by a thermal efficiency:

$$COP_T = \eta_T = \frac{l_s - l_{LP}}{q_H}. \tag{1}$$

Where specific parameters are given for kg of WF: l_S - work of turbine, l_{LP} - liquid pump work, and q_H heat supply.
However, $COP_T = \eta_T$ could be informative in the only case of identical temperature range T_H to T_L. Meanwhile, data presented above shows that best performance for selected WF could be achieved with different cycle configuration that demand different level of T_H for vapor superheat.
More general criteria is known as Carnot Efficiency (CEF), which compares a given cycle efficiency with the ideal Carnot cycle operating at the same conditions. Carnot efficiency is identical to η_E - exergetic efficiency and can be presented as:

$$CEF = \eta_E = \frac{l_s - l_{LP}}{q_H\left(\frac{T_H}{T_L} - 1\right)}, \text{ if } T_L \text{ equals to ambient temperature } T_A. \tag{2}$$

CEF is always in a rage of CEF = 0…1 and can be presented in a form of:

$$CEF = 1 - \frac{D_\Sigma}{E_Q} = 1 - \frac{D_{INT} + D_{EXT}}{E_Q}. \tag{3}$$

Summarized exergy loss in a real cycle (D_Σ) includes two constituents: intrinsic (D_{INT}) and (D_{EXT}) extrinsic losses. Intrinsic losses (D_{INT}) depend on thermodynamic processes of the cycle and WF properties. Extrinsic loss (D_{EXT}) depends on the equipment performance, which can be varied with cost considerations.
Both criteria are taken for further comparison, which can be conducted with different assumption. The maximal performance is related to the highly idealized cycle, which has a negligible small extrinsic loss $D_{EXT} = 0$ and includes D_{INT} only. CEF and COP_T of the highly idealized cycle depend on the WF properties, and cycle configuration only.

4. MODELING DATA ON COMPARATIVE PERFORMANCE OF LTC

Comparative data on the performance of WF has been obtained for a simplified LTC model at T_H = const and T_L = const. Group of selected WF include substances with normal saturation temperature

T_{S0} in a range of – 15 C to + 36 C. This allows modeling of LTC performance when operating at wide range of high pressure P_H and low pressure P_L. Also the selected WF provides $P_L > 1$ at, which is important avoiding vacuum. For R-245fa up graded data is taken from [7], for other WF – from [11].

Table 1. General Data for the selected WF

WF	TLV, ppm	LFL, %	ODP	GWP	T_{SO}, ^oC
R-21	10	0	0.01	210	8.9
R-245fa		0	0	820	15.1
R-601	600	1.5	0	11	36.2
R-600	800	1.8	0	20	-0.5
R-134a	1000	0	0	1200	-26.1

Results are presented in Table 2 and Table 3 for different sets of temperatures T_H and T_L.
The left side of each table presents information for a highly idealized cycle a maximal available capacity – a turbine specific work, and coefficients of efficiency COP_T and CEF. Such a cycle includes only intrinsic exergy loss, assuming that no extrinsic losses related to the equipment design. This means that hydraulic pressure drop, minimal temperature difference in heat exchangers; heat losses through the insulation are negligibly small. It is also assumed that cycle operates with ideal turbine and liquid pump.
At T_H = 100 C and T_L = 30 C for all WF presented in the Tables, thermal efficiency is in a range of COP_T = 17…20 % and CEF = 60…65 %. As long as In this analysis the heat source temperature T_H = const. This causes exergy loss - $D_{INT} > 30$ %, related to preheating of WF before evaporating. Lowering T_A down to 15 C increases both COP_T and the turbine work. However, CEF reduces due to temperature difference and heat load increase at WF preheating.
The right side in the Tables shows parameters that affect equipment design and characteristics related to size and cost of the equipment. WF properties influence on the internal turbine efficiency evaluated by modeling, which predicts a relatively high performance up to 0.86. Lower efficiency for R-600 and R-134a is due to small volumetric flow rates and correspondingly lower blade heights. It is assumed that the turbine expansion process is taking place in the field of superheated vapor.
For Pentane (R-601) volumetric flow rate downstream of turbine is considerably higher compared to R-21 and R-245fa. This leads to increasing of dimension and mass of discharge pipelines and condensers. Another draw back of Pentane associates with an increased heat load related to vapor fraction cooling in the condenser.
Results lead to a conclusion that a new available refrigerant HFC R-245fa (ODP = 0), which was designed to substitute HCFC R-123 (ODP = 0.014), matches to the LTC requirements better compared to the others WF. Obtained data on the performance are identical to those obtained by G. Zyhowski [7].
Meanwhile, R-245fa has some drawbacks. One of them is related to toxicity, which matches to a safety group B, according to the ASHRAE classification [12]. It says that WF can be toxic at TLV level below 400 ppm. Another drawback is connected to a relatively low pressure in the condenser, especially at low condensing temperature.

Table 2. Maximal efficiency of LTC at T_H = 100 ^{0}C, T_L = 30 ^{0}C

Working fluid	Characteristics of the LTC performance						
	Maximal – Extrinsic Performance				Affecting equipment		
	COP_T (CEF) η_T (η_E), %	Turbine Specific Work, kJ/kg	LTC Pressure Ratio P_H /P_L, bar	Mass flow rate-G_M, kg/kW-h	Expected internal relative turbine efficiency, %	Volumetric flow rate (outlet turbine) -G_V, m^3/kW-h	Fraction of Heat Load for Vapor Cooling in Condenser- %
R-21	16.3* (70)	45.6	13.2 / 2.14	78.9	0.86	8,5	0
R-245fa	15.2 (66)	37.5	12.8 / 1.8	96	0.86	10,1	6,4
Pentane (R-601)	15.3 (66)	73.3	5.9 / 0.82	49.1	0.865	21,7	9,5
Butane (R-600)	15 (65)	69.9	15.3 / 2.8	51.5	0.825	7,6	6,2
R-134a	14* (61)	31.9	39.7 / 7.7	112.9	0.815	3,0	0

Table 3. Maximal efficiency of LTC at T_H = 100 ^{0}C, T_L = 15 ^{0}C

Working fluid	Characteristics of the LTC performance						
	Maximal – Extrinsic Performance				Affecting equipment		
	COP_T (CEF) η_T (η_E), %	Turbine Specific Work, kJ/kg	LTC Pressure Ratio P_H /P_L, bar	Mass flow rate-G_M, kg/kW-h	Expected internal relative turbine efficiency, %	Volumetric flow rate (outlet turbine) -G_V, m^3/kW-h	Fraction of Heat Load for Vapor Cooling in Condenser- %
R-21	19.7* (67)	59.3	13.2 /1.3	60.7	0.86	10.7	0
R-245fa	18 (61)	47.5	12.8 / 1	75.8	0.86	13.9	7.4
Pentane (R-601)	18.2 (62)	96.8	5.9 / 0.5	37.2	0.86	28.3	9.8
Butane (R-600)	17.9 (61)	89.6	15.3 /1.8	40.2	0.82	9.4	6.4
R-134a	16.9* (57)	41.8	39.7 / 4.9	86.1	0.81	3.6	0

These drawbacks could be potentially reduced with mixed working fluids (MWF). Mixed refrigerant technology was efficiently used in developing new refrigerants to substitute CFC according to the Montreal Protocol. A list of mixed refrigerants with normal boiling temperature in a range of –30C to + 30 C consists of more than 50 items [11]. Mixed refrigerant technology is also successfully used in developing small Cryogenic coolers and industrial plants for air separation and natural gas liquefaction [13,14].

Table 4 presents data on the expecting properties of new MWF for LTC compared to R-21 and R-245fa. The table demonstrates a possibility compromising properties of pure WF matching certain requirements within geothermal technology.

In spite of international efforts in research and developments of working fluids, there has not been found a new pure substance, which could be used as refrigerant efficiently operating in heat pumps based on traditional equipment. A modern trend in this development is associated with following directions [15,16].

- Applications of natural refrigerants (especially in Europe) such as HC, NH3, Water and CO2. However, carbon dioxide technology needs new equipment operating at elevated pressure up to 100 at. This complicates applying it to large-scale equipment.
- Some opportunities are associated with synthesis of Hydro-Fluoro-Ethers. However, toxicity issues and cost considerations are of real concern in this case.
- Using multi-component refrigerants MWF is proven to be a cheap and efficient way in designing working fluids for different applications. It can be also efficiently applied to geothermal technology.

In general, independent of which way to go, hermetically sealed equipment must be used for all potential solutions. The reasons associated to issues that are related to: flammability – for HC, toxicity – Ethers, GWP increase- FC and HFC use. CHFC is banned with Montreal Protocol.

Table 4. Data for New MWF for LTC operating at T_H = 100 C, T_L = 30 C.

Working Fluid	R-21	R-245fa	MWF-1	MWF-2
P_H/P_L, bar	11/2.2	10.3/1.8	12.1/2.4	16.2/3.0
MM	103	134	114	90
ODP	0.01	0.00	< 0.01	0.00
GWP (100 yr.)	210	950	< 600	< 500

5. CONCLUSIONS

1. Properties of working fluid for low-temperature cycle applied to geothermal technology are essentially influenced on the efficiency, operational parameters and equipment designing.
2. R-245fa is a new environmentally friendly, commercially available working fluid may be efficiently used in LTC. Carnot Efficiency of highly idealized cycle could be as high as 0.60 … 65 at T_H= 100 C и T_L = 30 …15 C.
3. Using multi-component working fluids MWF promise to be efficient in developments of low temperature cycles for geothermal technology.
4. Decreasing lower temperature T_L of the cycle from 30 to 15^o C enhances specific power production and thermal efficiency of the cycle. However, it reduces Carnot Efficiency from 0.66 to 0.61. This is due to non-optimal temperature profiles in the preheating of the WF before evaporating at T_H = const, selected for this cycle model .

ABBREVIATIONS:

GPS – geothermal power station;
GPW – geothermal power plant;
LTC – low temperature cycle;
COP – coefficient of performance;
COP_T – thermal coefficient of performance;
CEF – Carnot efficiency;
WF – working fluid of LTC;
“pure” – single component fluid;
MWF – multi-component WF;

ODP - Ozone depletion potential;
GWP – global warming potential.

REFERENCES

1. Kanayev A.A., Kryshev V.V., Shirkov B.A. et al. Single-shaft water-freon high capacity turbo-installations // M.: Energomashinostroyeniye, 1967. No. 10. P. 30-34 (in Russian).

2. Moskvichova A.L., Popov A.Ye. Geothermal power plant at Paratunka river // Geothermics, 1970, Vol. 2, P. 1561-1571 (in Russian).

3. Rozenfeld L.M., Tkachov A.G. Refrigeration machines and instruments. M.: GITL, 1955 (in Russian).

4. Kalina A.I. Combined-Cycle System with Novel Bottoming Cycle, Journal of Engineering for Gas Turbines and Power, 106, 737-742, 1984.

5. Arni Ragnarsson**.** Geothermal Development in Iceland 1995-1999 // Proceedings World Geothermal Congress 2000.

6. Sones, R. and Krieger, Z. “Case history of the binary power plant development at the Heber, Califormia geothermal resource”, Proceedings World Geothermal Congress, 2000, Kyushu, Japan.

7. Zyhowski, G.,”HFC-245fa in Organic Rankine Cycle Applications”//Proceedings of 21st IIR International Congress of Refrigeration// Washington D.C.,USA , 2003.

8. Povarov O.A., Saakyan V.A., Nikolski A.I. et al. Binary power plants / Tyazholoye mashinostroyeniye, 2003. N0. 8, P. 13-15 (in Russian).

9. Popovski, K and. Sanner, B. ”Low-enthalpy power generation with ORC-Turbo-generator…” /Proceedings of the International Summer School Conference/ Germany 2001.

10. Kanayev A.A., Kopp I.Z. Non-water steams in power engineering industry. L.: Mashinostroyeniye, 1973 (in Russian).

11. Calm J. “Property, Safety, and Environmental Data for Alternative Refrigerants” // Earth Technologies Forum, Washington D.C.-1998г.

12. ASHRAE HANDBOOK, Fundamentals, 1997.

13. Boiarski, M. et al. “Optimal Design and Generalized Performance of Throttle-Cycle Coolers Operating with Mixed Refrigerants”// Proceedings of 21st IIR International Congress of Refrigeration// Washington D.C.,USA , 2003.

14. Boiarski, M., Brodianski, V., Longsworth, R., “Retrospective of Mixed-Refrigerant Technology and Modern Status of Cryocoolers Based on One-Stage, Oil-Lubricated Compressors”, Advances in Cryogenic Engineering, Plenum Press, New York: Vol.43 (1998) pp.1701 – 1708.

15. Refrigerants for the 21st Century, ASHRAE/NIST Refrigerant Conference, Gaithersburg, Maryland, USA, 1997.

16. Proceedings of 21st IIR International Congress of Refrigeration//Washington D.C., USA, 2003.