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ESTIMATING THE EFFICIENCY OF HET SYSTEMS USING CARBON DIOXIDE AND AMMONIA AS REFRIGERANTS

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Results of the comparison made between total capacities of horizontal evaporator tube (HET) systems (Russian brand name "GET" systems for thermosyphons) using dioxide and ammonia as the working fluids has revealed that the total capacity of HET systems charged with carbon dioxide is always higher, against the systems charged with ammonia.

Permafrost, HET, seasonal refrigeration system, refrigerant, ammonia, carbon dioxide

INTRODUCTION

Systems for ground temperature stabilization, or ground cooling systems, with horizontal evaporator tubes (for short HET systems) are used to maintain below freezing temperatures in permanently frozen soils of the structures' bases during the winter season. A schematic representation of the system is shown in Fig. 1. The mathematical model describing an HET system operation is provided in [*Anikin, 2009*]. The mathematical modeling for HET systems using ammonia as the working fluid (coolant) is discussed in [*Anikin et al., 2011*]. While different coolants can be used as the working fluid for such systems, not all coolants are capable to ensure the system's performance. The analysis provided in [*Anikin, Spasennikova, 2014*] concerns several coolants applicable in such systems, among them: carbon dioxide, ammonia, Freon 22, freon 12, freon 142, freon 21, freon 11, methylene chloride, acetone, freon 113, methanol. The coolants were analyzed in the context of the Vankor oil-gas field development, with the air temperatures measured at the Igarka weather station. According to the conclusions the authors have arrived thereat, such coolants as methylene chloride, acetone, freon 113 and methanol fail to ensure the system's operation during the winter season. Whereas carbon dioxide and ammonia have proven to be more effective.

The systems of this type – thermosyphons – which use ammonia as the working fluid (coolant) developed by *FundamentStroiArkos* have been widely used in Russia to preserve and cool permafrost. Establishing the upper and lower limits for thermal loads for an HET system working on ammonia was discussed in [*Melnikov et al., 2017*]. The Institute of Earth's Cryosphere, Siberian Branch of the Russian Academy of Sciences has developed seasonal cooling systems working on carbon dioxide. These start working once the ground becomes a few tenths of a degree warmer than the overlying atmosphere (the temperature difference is almost zero), while systems charged with ammonia are shown to be less temperature-sensitive, inasmuch as they start working when the ground is a few degrees warmer than the atmosphere [*Anikin, Spasennikova, 2014*]. Thus, the operating time of the ground stabilization cooling system charged with carbon dioxide during the winter season is significantly longer than the operating time of the system using ammonia as the working fluid. Accordingly, the capacity of the system charged with carbon dioxide can be significantly greater than that of charged with ammonia.

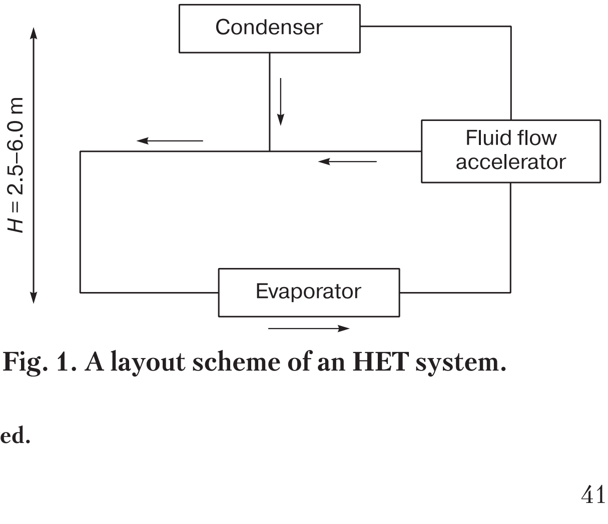

Fig. 1. A layout scheme of an HET system.

Table 1. **The relationship between the system's cooling capacities for carbon dioxide and ammonia at a preset temperature**

H, m	Δ_{CO_2}	Δ_{am}	$t_{gr} - t_{air}$									
			1	2	3	4	5	6	7	8	9	10
1	2	3	4	5	6	7	8	9	10	11	12	13
Condenser temperature –30 °C												
2.5	0.54	2.86	∞	∞	17.17	3.02	2.08	1.74	1.56	1.45	1.38	1.32
3.0	0.65	3.43	∞	∞	∞	5.85	2.77	2.08	1.78	1.61	1.50	1.42
3.5	0.76	4.00	∞	∞	∞	13526.82	4.24	2.62	2.08	1.81	1.65	1.54
4.0	0.87	4.57	∞	∞	∞	∞	9.63	3.59	2.52	2.08	1.84	1.68
4.5	0.98	5.14	∞	∞	∞	∞	∞	5.85	3.24	2.46	2.08	1.86
5.0	1.09	5.71	–	∞	∞	∞	∞	17.17	4.60	3.02	2.41	2.08
5.5	1.20	6.29	–	∞	∞	∞	∞	∞	8.12	3.97	2.87	2.37
6.0	1.31	6.86	–	∞	∞	∞	∞	∞	39.74	5.85	3.59	2.77
6.5	1.42	7.43	–	∞	∞	∞	∞	∞	∞	11.51	4.83	3.34
7.0	1.52	8.00	–	∞	∞	∞	∞	∞	∞	13526.82	7.47	4.24
7.5	1.63	8.57	–	∞	∞	∞	∞	∞	∞	∞	17.17	5.85
8.0	1.74	9.14	–	∞	∞	∞	∞	∞	∞	∞	∞	9.63
8.5	1.85	9.71	–	∞	∞	∞	∞	∞	∞	∞	∞	28.47
Condenser temperature –20 °C												
2.5	0.42	1.93	∞	22.43	2.41	1.73	1.49	1.37	1.30	1.25	1.21	1.19
3.0	0.50	2.32	∞	∞	3.65	2.08	1.68	1.49	1.39	1.32	1.27	1.24
3.5	0.58	2.70	∞	∞	8.09	2.63	1.92	1.64	1.49	1.40	1.34	1.29
4.0	0.67	3.09	∞	∞	∞	3.65	2.27	1.83	1.62	1.49	1.41	1.35
4.5	0.75	3.47	∞	∞	∞	6.17	2.78	2.08	1.77	1.60	1.49	1.42
5.0	0.83	3.86	∞	∞	∞	22.43	3.65	2.41	1.96	1.73	1.59	1.49
5.5	0.91	4.24	∞	∞	∞	∞	5.41	2.90	2.21	1.89	1.70	1.58
6.0	1.00	4.63	∞	∞	∞	∞	10.83	3.65	2.53	2.08	1.83	1.68
6.5	1.08	5.02	–	∞	∞	∞	∞	5.00	2.98	2.32	1.99	1.79
7.0	1.16	5.40	–	∞	∞	∞	∞	8.09	3.65	2.63	2.18	1.92
7.5	1.25	5.79	–	∞	∞	∞	∞	22.43	4.75	3.05	2.41	2.08
8.0	1.33	6.17	–	∞	∞	∞	∞	∞	6.86	3.65	2.71	2.27
8.5	1.41	6.56	–	∞	∞	∞	∞	∞	12.69	4.57	3.11	2.50
Condenser temperature –10 °C												
2.5	0.32	1.35	∞	2.58	1.62	1.39	1.28	1.22	1.18	1.15	1.13	1.12
3.0	0.38	1.62	∞	4.25	1.90	1.52	1.37	1.28	1.23	1.19	1.17	1.15
3.5	0.45	1.89	∞	14.01	2.30	1.68	1.46	1.35	1.28	1.24	1.20	1.18
4.0	0.51	2.16	∞	∞	2.96	1.90	1.58	1.43	1.34	1.28	1.24	1.21
4.5	0.57	2.43	∞	∞	4.25	2.18	1.72	1.52	1.41	1.33	1.28	1.25
5.0	0.64	2.70	∞	∞	7.84	2.58	1.90	1.62	1.48	1.39	1.33	1.28
5.5	0.70	2.97	∞	∞	73.20	3.20	2.12	1.75	1.56	1.45	1.38	1.32
6.0	0.77	3.24	∞	∞	∞	4.25	2.40	1.90	1.66	1.52	1.43	1.37
6.5	0.83	3.51	∞	∞	∞	6.45	2.80	2.08	1.77	1.60	1.49	1.41
7.0	0.89	3.78	∞	∞	∞	14.01	3.36	2.30	1.90	1.68	1.55	1.46
7.5	0.96	4.05	∞	∞	∞	∞	4.25	2.58	2.05	1.78	1.62	1.52
8.0	1.02	4.32	–	∞	∞	∞	5.84	2.96	2.23	1.90	1.70	1.58
8.5	1.08	4.59	–	∞	∞	∞	9.50	3.48	2.45	2.03	1.79	1.65
Condenser temperature 0 °C												
2.5	0.25	0.97	29.73	1.71	1.36	1.24	1.18	1.15	1.12	1.10	1.09	1.08
3.0	0.29	1.17	∞	2.05	1.48	1.31	1.23	1.18	1.15	1.13	1.11	1.10
3.5	0.34	1.36	∞	2.61	1.62	1.39	1.28	1.22	1.18	1.15	1.13	1.12

Table 1, continued

1	2	3	4	5	6	7	8	9	10	11	12	13
4.0	0.39	1.56	∞	3.65	1.81	1.48	1.34	1.26	1.21	1.18	1.16	1.14
4.5	0.44	1.75	∞	6.34	2.05	1.58	1.40	1.31	1.25	1.21	1.18	1.16
5.0	0.49	1.95	∞	29.73	2.39	1.71	1.48	1.36	1.29	1.24	1.21	1.18
5.5	0.54	2.14	∞	∞	2.87	1.86	1.56	1.42	1.33	1.27	1.23	1.20
6.0	0.59	2.34	∞	∞	3.65	2.05	1.66	1.48	1.38	1.31	1.26	1.23
6.5	0.64	2.53	∞	∞	5.07	2.29	1.77	1.55	1.42	1.35	1.29	1.25
7.0	0.69	2.73	∞	∞	8.53	2.61	1.90	1.62	1.48	1.39	1.33	1.28
7.5	0.74	2.92	∞	∞	29.73	3.03	2.05	1.71	1.54	1.43	1.36	1.31
8.0	0.79	3.12	∞	∞	∞	3.65	2.24	1.81	1.60	1.48	1.40	1.34
8.5	0.84	3.31	∞	∞	∞	4.61	2.47	1.92	1.67	1.53	1.44	1.37

Note. The symbol "∞" indicates that the system does not work on ammonia; the dash "–" means that the system uses neither carbon nor ammonia as the working fluid; H is the condenser height above the evaporator, m; Δ_{CO_2} and Δ_{am} are the differences in the condenser and ground temperatures for the system working on carbon dioxide and ammonia, respectively, °C; t_{gr} is the ground temperature, °C; t_{air} is the air temperature, °C. The values for H are usually in the range from 2.5 to 6.0 m ($H < 2.5$ m not occurred in practice); for the *FundamentSroiArkos* systems $H = 6$ m.

CALCULATIONS

The system's capacity (heat output) is expressed by the following expression [*Anikin, Spasennikova, 2014*]:

$$W = \left(t_c - t_{air}\right) S\eta\alpha = \left(\left(t_c - t_{gr}\right) + \left(t_{gr} - t_{air}\right)\right) S\eta\alpha, \quad (1)$$

where t_c is the condenser temperature; t_{gr} is the ground temperature at the interface with the evaporator tube; t_{air} is the air temperature; S is the total area of the finned section; η is the coefficient of efficiency of the condenser fins; α is the heat transfer coefficient for the fins;

$$W_{am} = \left(-\Delta_{am} + \left(t_{gr} - t_{air}\right)\right) S\eta\alpha; \quad (2)$$

$$W_{CO_2} = \left(-\Delta_{CO_2} + \left(t_{gr} - t_{air}\right)\right) S\eta\alpha; \quad (3)$$

for ammonia $\left(t_c - t_{gr}\right) = -\Delta_{am}$, for carbon dioxide $\left(t_c - t_{gr}\right) = -\Delta_{CO_2}$.

The values for Δ_{CO_2}, Δ_{am} are calculated using the formula [*Anikin, Spasennikova, 2014*]

$$\Delta_{CO_2/am} = \frac{\rho_L g H}{dP_{sat}/dt},$$

where ρ_L is the liquid coolant density at a specified temperature; g is gravity; P_{sat} is the pressure of saturated vapors at a specified temperature; H is the condenser height above the evaporator.

By dividing (3) by (2), we obtain

$$\frac{W_{CO_2}}{W_{am}} = \left[1 - \frac{\Delta_{CO_2}}{t_{gr} - t_{air}}\right]\left[1 - \frac{\Delta_{am}}{t_{gr} - t_{air}}\right]^{-1}.$$

The condition to be fulfilled for the ground freezing is: $t_{air} < t_{gr}$.

Table 1 shows the ratios of heat outputs (i.e. the systems' capacities) for carbon dioxide and ammonia at different condenser temperatures, taking into account difference in ground and air temperature temperatures, and the distance between the evaporator and the condenser.

It follows from Table 1 that if the system works both on carbon dioxide and ammonia, the capacity of this system charged with carbon dioxide is always greater as compared to its using ammonia as the working fluid.

CONCLUSIONS

It has been shown that the thermal capacity of an HET system working on carbon dioxide is always higher than the capacity of the same system using ammonia as the working fluid. This primarily is explained by the fact that the derivative of saturated vapor pressure with respect to temperature is always higher for carbon dioxide than for ammonia. As the distance between the evaporator and the condenser increases with affiliated increase in hydrostatic pressure, the ratio of hydrostatic pressure to the derivative of saturated vapor pressure with respect to temperature for carbon dioxide is therefore also always less than for ammonia.

With an increase in the condenser temperature, the region where the system works neither on carbon dioxide nor ammonia explicably decreases. The system charged with carbon dioxide works at a greater distance between the condenser and the evaporator at a 1 °C difference between ground and air temperatures, while it fails to operate on ammonia.

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