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Heat Integration of Ammonia Refrigeration Cycle into Buildings Heating Systems in Buildings

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Abstract—The possibility of utilizing the low-potential heat of the ammonia refrigeration cycle has been shown. The design of an energy-saving heat exchangers network to heat water and air in municipal buildings has been proposed. The possibility of increasing the pressure of ammonia with the purpose of improving the heat recovery in the system and reducing the load of the heating and cooling systems was considered. The minimum temperature difference in the heat exchangers network was selected. The economic efficiency of the retrofit project was estimated.

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INTRODUCTION

The considerable increase in the cost of energy sources and the level of carbon dioxide waste emitted into the environment requires the development of solutions for improving the energy efficiency of existing processes [1]. The reduction of the consumption of energy sources and the level of hazardous emissions into the atmosphere is directly associated with the operability and sustainability of industrial plants [2]. This problem is felt most acutely in the manufacturing and processing industries of national economy. For these industries, the creation of these methods has long been among the priorities of development [3]. These methods and their industrial applications are represented in [4, 5]. The first of these [4] are associated with the construction of complex mathematical models of chemical-engineering systems and the use of a great number of variables. The others [5] use the system approach to improve the energy efficiency of industrial plants. For the housing and utility sector, this problem is no exception, especially when it concerns low-potential heat sources. The efficiency of the application of technologies for the utilization of waste heat is estimated in [6]. These sources can be used to satisfy the need for heating in the systems of buildings. One of the most efficient methods for using low-potential heat is the application of heat pumps [7]. In more details, the application of heat pumps and the estimation of their efficiency are described in [8, 9]. The review of the application of heat pumps and their efficiency is given in [8]. The results of the application of heat pumps in the United States are described in [9].

The refrigeration systems of supermarkets use ammonia refrigeration machines in systems for freezing, cooling, and storing food. Supermarkets are usually located near densely populated residential blocks. During the operation of similar ammonia units, a great deal of low-potential heat is not used and is wasted into the atmosphere through the cooling system. On the other hand, there is a need to deliver heat in the heating, conditioning, and water-supply systems of buildings. However, the temperature regimes of consumers are frequently such that the utilization of waste heat is always unreasonable. The technology of the utilization of low-potential heat for the other industrial needs is described in [10]. However, it is difficult to find an optimal solution without the detailed analysis of a process stream system, heat exchange at different temperature levels, and a heat recovery system. One of the most efficient methods of attaining optimal efficiency is pinch analysis [11–13], which is based on the thermodynamic analysis of a process stream system and the creation of plant flowsheets with consideration for the cost of utilities and equipment. This methodology has a rather wide application in the production and storing of food products, as is shown in the papers of different researchers [1]. Some of these researchers consider the integration of heat machines to be a multilevel problem [14]. The others demonstrate the efficiency of the arrangement of heat machines in combination with the integration of the separation and cogeneration systems [15].

The possibility of integrating the ammonia refrigeration cycle into the heating system of a cheese production plant was shown previously in [16], which led to a 65% decrease in the expenditures on

Table 1. Parameters of process streams of original process

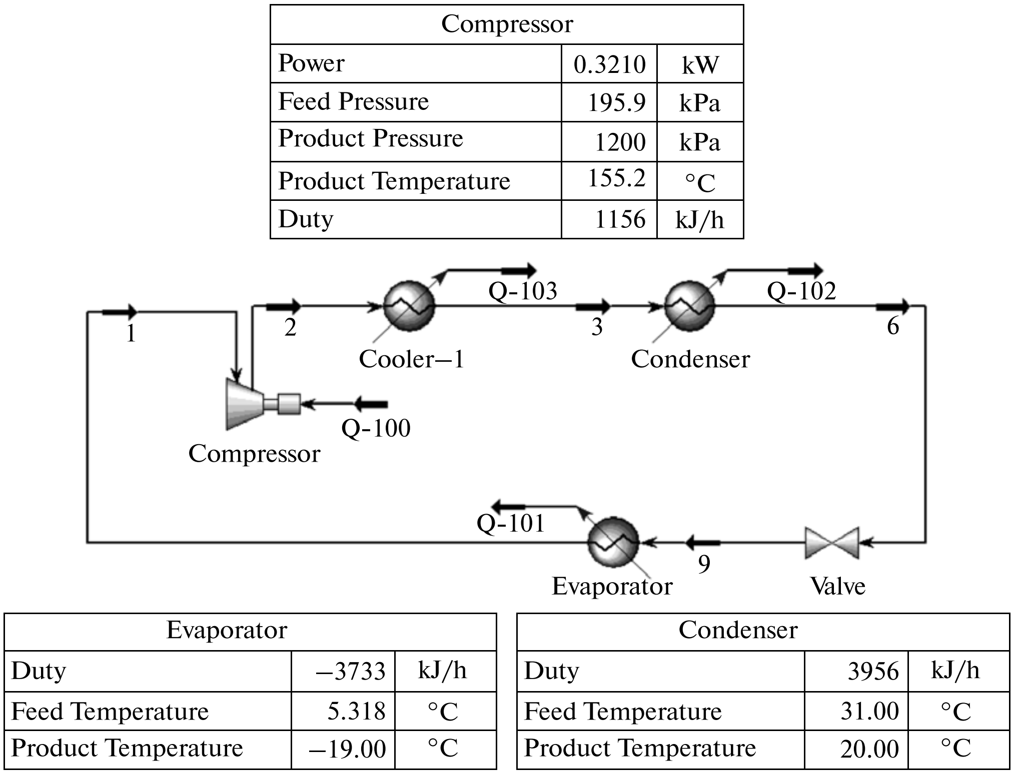
No.	Stream name	Type	t_S, °C	t_T, °C	G, t/h	C_p, kJ/(kg K)	r, kJ/kg	CP, kW/K	ΔH, kW
1	Ammonia cooling	Hot	155	30	3.194	3.250	–	2.883	360.43
	Ammonia condensation	Hot	30	30	3.194	–	1146	–	1016.76
	Cooling of liquid ammonia	Hot	30	20	3.194	4.750	–	4.214	42.14
2	Water heating	Cold	15	60	15.000	4.190	–	17.458	785.63
3	Air heating	Cold	10	30	50.000	1.005	–	13.958	279.17
4	Air for curtain heaters	Cold	10	55	25.000	1.005	–	6.979	314.06

utilities at the expense of improved heat integration. In the given work, we study the possibility of utilising the condensation heat of a supermarket refrigeration machine for existing heat consumers. The possibility of using the overheating and condensation heat of ammonia is considered. Further, we study the possibility of the additional compression of ammonia for the most complete utilization of the condensation heat of ammonia. The process integration methodology, which allows us to reduce the energy consumption and construct a heat exchange network that takes into consideration the minimum total reduced cost is used for analysis.

PROCESS MODELING

Supermarket refrigeration units are conventional ammonia refrigeration machines [17]. The obtained process data allows us to construct a computer model of the studied refrigeration unit using the UniSim Design software [18]. This makes it possible to refine the temperature, pressure, and flow rate of the cooling agent and obtaining the unavailable thermophysical properties. The pressure of ammonia at the inlet and outlet of a compressor are equal to 196 and 1200 kPa, and the unit's refrigerating capacity is 3956 kJ/h. The technological streams of the studied process and their thermophysical properties are given in Table 1.

The model of the ammonia refrigeration cycle is illustrated in Fig. 1. At this stage, the overheating and condensation heat of ammonia is withdrawn with cooling water and wasted into the environment. This can clearly be seen from the Composite Curves of the existing process (Fig. 2). The heating of all the cold streams



Compressor		
Power	0.3210	kW
Feed Pressure	195.9	kPa
Product Pressure	1200	kPa
Product Temperature	155.2	°C
Duty	1156	kJ/h

Evaporator		
Duty	–3733	kJ/h
Feed Temperature	5.318	°C
Product Temperature	–19.00	°C

Condenser		
Duty	3956	kJ/h
Feed Temperature	31.00	°C
Product Temperature	20.00	°C

Fig. 1. UniSim model of ammonia refrigeration cycle.

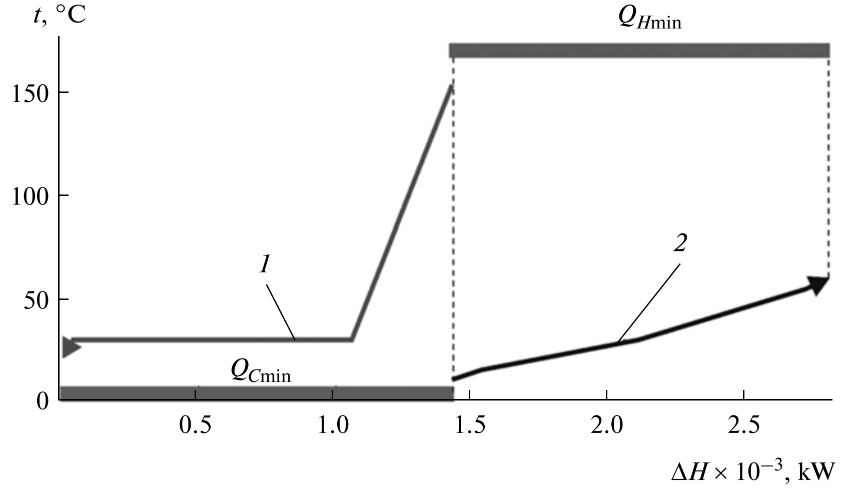


Fig. 2. Composite Curves of the existing system of heat streams: (*1*) hot, (*2*) cold.

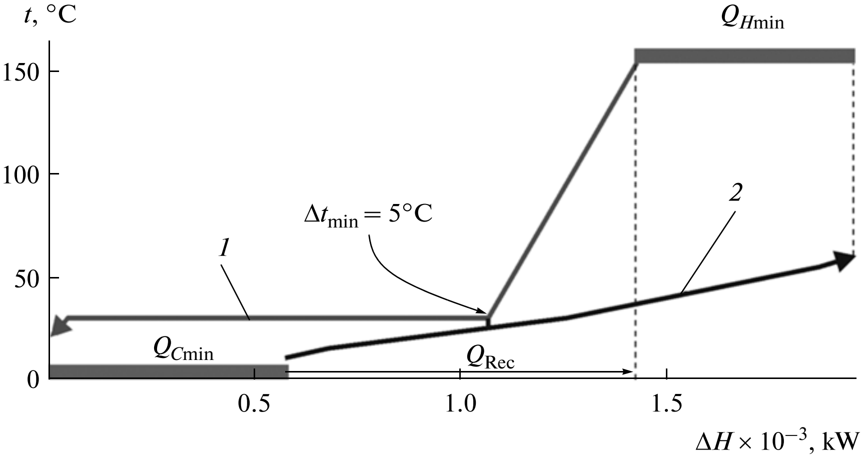


Fig. 3. Composite Curves of original process for $\Delta t_{\min} = 5°C$: (*1*) hot, (*2*) cold.

requires 1379 kW, the cooling of the hot streams represented by the hot composite curve needs 1419 kW, and the heat recovery region is completely absent.

HEAT INTEGRATION

Integration of Refrigeration Cycle

The shift of Composite Curves towards each other up to the point of attaining the admissible minimum temperature difference ($\Delta t_{\min}$) between the process streams makes it possible to obtain the maximum recovery of heat energy in the system.

The admissible minimum difference between the temperatures of heat transfer agents for the existing heat exchange equipment is 5°C. The composite curves of the process with a minimum temperature approach of 5°C are shown in Fig. 3.

The composite curves how that the recovery of heat energy in the existing system of process streams is 849 kW at $\Delta t_{\min} = 5°C$, and the power of hot and cold utilities is 530 and 570 kW, respectively. It can be seen that the overheating heat of ammonia and its condensation heat are partially utilised. The condensation heat cannot be utilized completely due to the structure of the composite curves and the location of the pinch point. To attain the target powers of hot and cold utilities and the best recovery of heat, it is necessary to use the network of heat exchangers. The constructed grid diagram of the arrangement of heat exchangers for the studied system of streams is shown in Fig. 4.

The grid diagram shows that the recovery of 849 kW of heat energy requires four heat exchangers, one of which must be located in the subsystem above the pinch point, while the others must be included into the subsystem below the pinch point. The power of hot and cold utilities amounts 530 and 570 kW, which is in com-

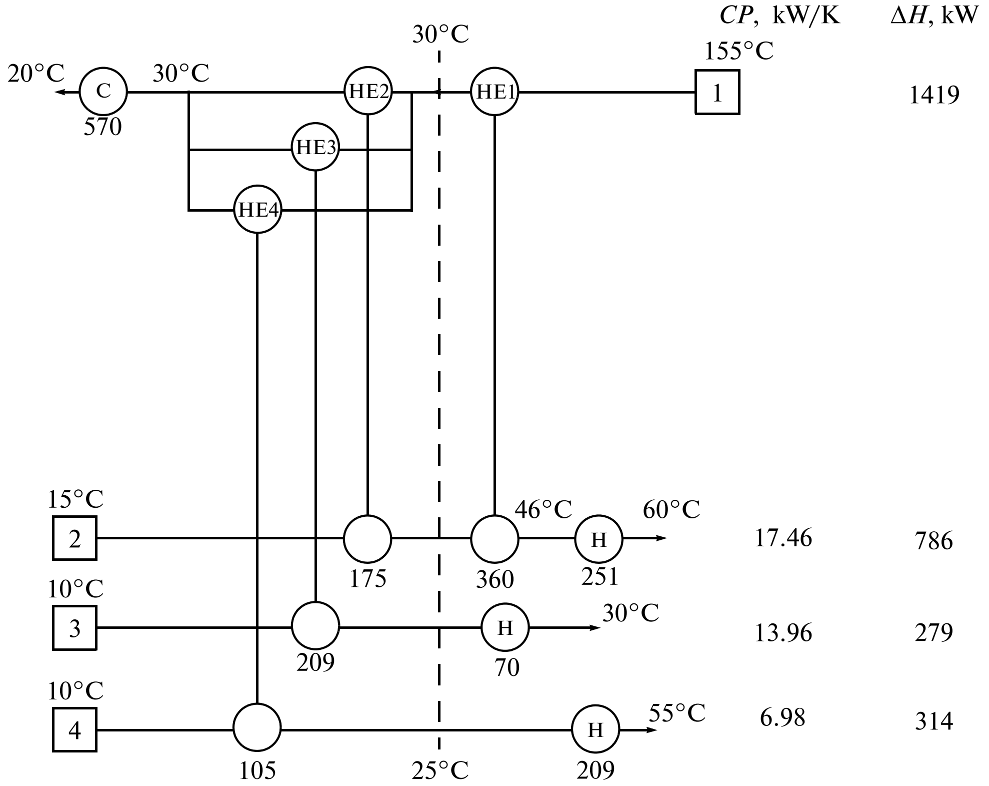


Fig. 4. Grid diagram of studied system of streams for $\Delta t_{\min} = 5°C$: HE1–4 are recuperative heat exchangers, C is a cooler, H is a heater, and dashed line indicates pinch point.

plete agreement with the composite curves. Since $\Delta t_{\min} = 5°C$ in the network of heat exchangers, we recommend applying plate-type heat exchangers which allow us to attain a small temperature drop at the ends of the heat exchanger. In this case, heat exchangers must be welded to the ammonia side due to its high toxicity. The estimated total area of the additional heat transfer surface will amount to 225 m^2. For the calculations in our work, we assume that the cost of installing a single heat exchanger and the cost of 1 m^2 of heat transfer area are equal to 5000 and 500 USD [19], respectively. In Ukraine, the cost of hot and cold utilities are approximately 350 and 35 USD per 1 kW/h, and the estimated payback period is 5 months.

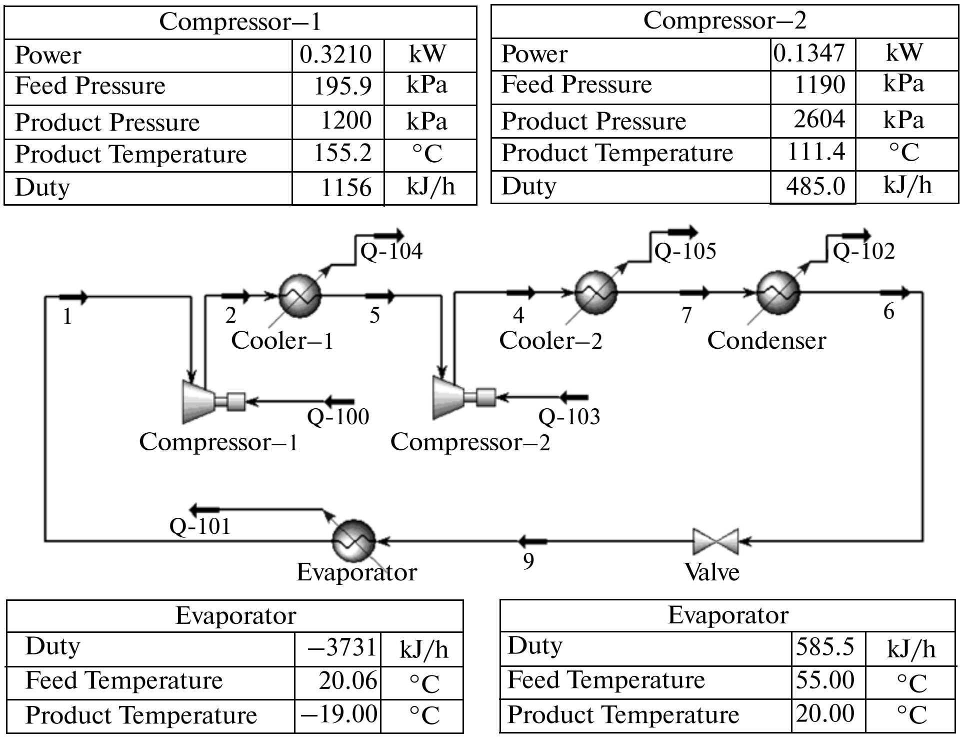
Additional Ammonia Compression

The additional analysis of the system of streams shows that, by increasing the condensation temperature, we can change the location of the pinch point and the shape of the composite curves (Fig. 3) and, in this fashion, raise the heat recovery potential [14]. Using UniSim Design software, a model has been constructed of a refrigeration machine with additional ammonia compression (Fig. 5). In the given flowsheet, the ammonia after the first compression stage is cooled from 125 to 30°C. Then, the stream enters the second compression stage and leaves it with a pressure of 2604 kPa and a temperature of 111°C. The ammonia is delivered from a compressor to cooling; condensation; and, thus, as in the first case, to throttling and evaporation.

The computer model allowed us to determine all of the characteristics of the ammonia stream in the refrigeration cycle with additional compression. This allowed us to form the table of the parameters of process streams to analyze the system of streams. The parameters of process streams that can be involved in heat integration are given in Table 2.

The composite curves of the nonintegrated process with additional compression are shown in Fig. 6. The required heat power will be equal to 1517 kW for cooling and 1378 kW for heating all cold streams.

Selection of Optimal $\Delta t_{\min}$. In the first case, we selected $\Delta t_{\min}$ from the minimum admissible difference, whereas, in the second case, we performed optimization calculations. To select the minimum temperature difference in the network of heat exchangers, we plotted the cost of the heat transfer area, the cost of utilities, and the total reduced cost as functions of $\Delta t_{\min}$ (Fig. 7). The curve of the total reduced cost has a minimum at $\Delta t_{\min} = 23°C$. However, in the range of $\Delta t_{\min}$ of 17–27°C, the total reduced cost changes slightly. In this case, the expenditures on utilities are lower at $\Delta t_{\min} = 17°C$. The minimum on the reduced utility cost curve (curve *1*, Fig. 7) is explained by the threshold character of the composite curves [11]. For threshold



Compressor–1		
Power	0.3210	kW
Feed Pressure	195.9	kPa
Product Pressure	1200	kPa
Product Temperature	155.2	°C
Duty	1156	kJ/h

Compressor–2		
Power	0.1347	kW
Feed Pressure	1190	kPa
Product Pressure	2604	kPa
Product Temperature	111.4	°C
Duty	485.0	kJ/h

Evaporator		
Duty	–3731	kJ/h
Feed Temperature	20.06	°C
Product Temperature	–19.00	°C

Evaporator		
Duty	585.5	kJ/h
Feed Temperature	55.00	°C
Product Temperature	20.00	°C

Fig. 5. UniSim model of ammonia refrigeration machine with additional compression.

problems, $\Delta t_{\min}$ is generally selected to be equal to Δt of the threshold. In our case, this value equals 17°C. Correspondingly, the selection of $\Delta t_{\min} = 17°C$ for designing a heat exchange network satisfies two requirements, namely, the total reduced cost of a design will be close to its minimum possible value, and $\Delta t_{\min}$ will correspond to its threshold value. Moreover, the prices on utilities constantly grow [20], and the selection of a smaller temperature difference will lead to lower expenditures in the future.

The composite curves of process streams with additional compression for $\Delta t_{\min} = 17°C$ are plotted in Fig. 8. The heat recovery amounts 1379 kW, the power of hot and cold utilities is reduced to 139 kW, and the need for hot utilities is no longer relevant, but the expenditures on the additional compression of ammonia are required.

Hence, the application of the additional compression of ammonia will allow us to satisfy the need for the heating of all the cold streams in the system with hot streams without utilities, but using the additional power of a compressor. The composite curves also show the location of the pinch point and its temperature that are required for constructing a network of heat exchangers with the use of a grid diagram.

Heat Exchangers Network. The developed grid diagram of a heat exchangers network for the integrated process with additional compression is shown in Fig. 9. The grid diagram consists of six recuperative heat exchangers with a total heat load of 1379 kW and two coolers for the cooling and condensation of ammonia.

Table 2. Parameters of process streams of system with additional compression

No.	Stream name	Type	t_S, °C	t_T, °C	G, t/h	C, kJ/(kg K)	r, kJ/kg	CP, kW/K	ΔH, kW
1	Ammonia cooling (first stage)	Hot	125	30	3.194	3.250	–	2.883	273.93
2	Ammonia cooling (second stage)	Hot	111	60	3.194	4.275	–	3.793	193.44
	Ammonia condensation	Hot	60	60	3.194	–	986.2	–	874.98
	Cooling of liquid ammonia	Hot	60	20	3.194	4.935	–	4.378	175.14
3	Water heating	Cold	15	60	15.000	4.190	–	17.458	785.63
4	Air heating	Cold	10	30	50.000	1.005	–	13.958	279.17
5	Air for curtain heaters	Cold	10	55	25.000	1.005	–	6.979	314.06

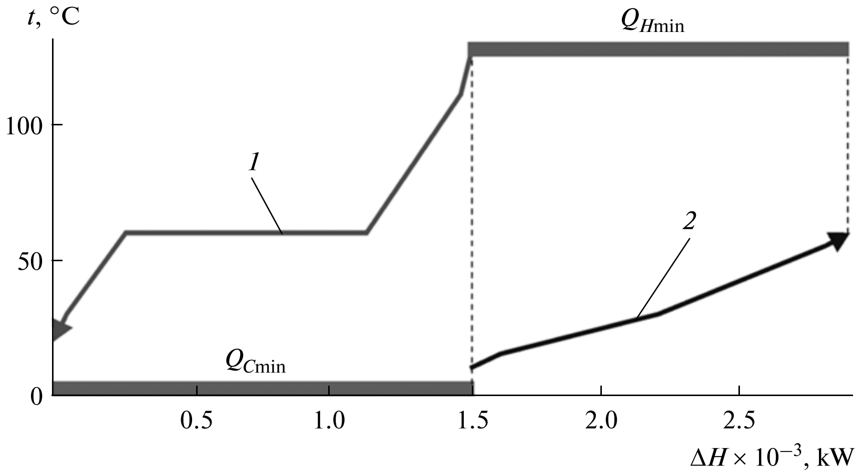


Fig. 6. Composite Curves of existing system of heat streams: (*1*) hot, (*2*) cold.

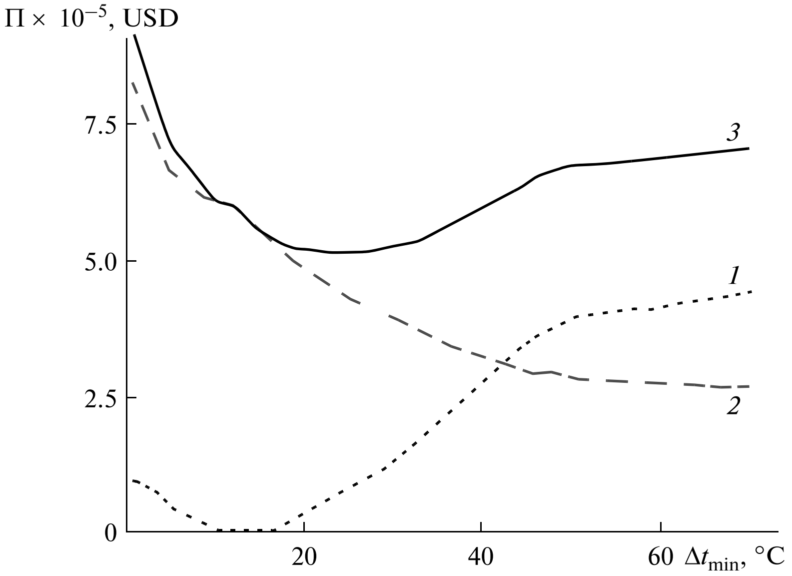


Fig. 7. Cost curves: (*1*) reduced cost of utilities, (*2*) reduced capital cost, (*3*) total reduced cost.

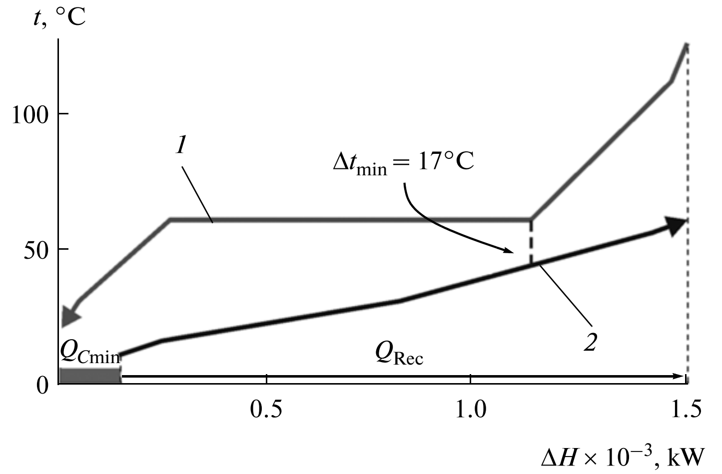


Fig. 8. Composite Curves of the process with additional ammonia compression for $\Delta t_{\min} = 17$°C and $Q_{Rec} = 1379$ kW: (*1*) hot, (*2*) cold.

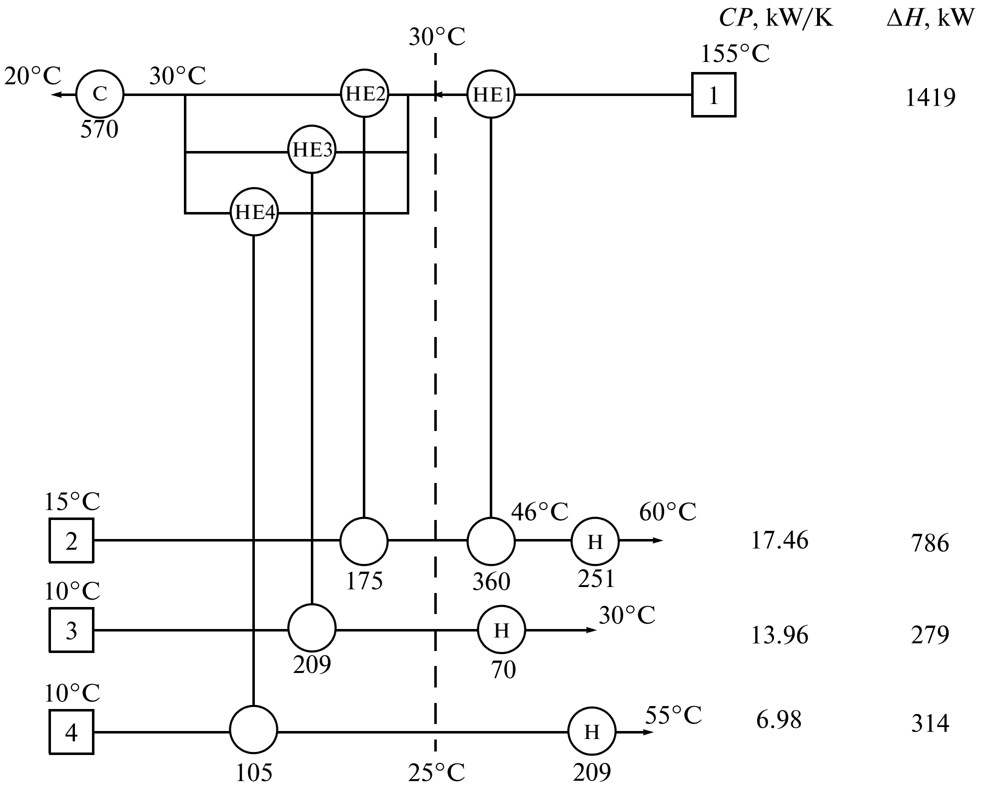


Fig. 9. Grid diagram of system of streams with additional ammonia compression for $\Delta t_{\min} = 17°C$: HT1–6 are recuperative heat exchangers, C is a cooler, H is a heater, and dashed line indicates pinch point.

The total heat transfer area of the additional equipment will be approximately 377 m^2, and we should note that heat exchangers of any design may be used in the system with additional compression due to the rather high minimum admissible temperature difference of 17°C. The operation of the system with additional compression also requires the installation of a compressor, which will consume 135 kW of electrical energy. The cost of a compressor will be approximately 50000 USD [6]. The cost of installing heat-exchange equipment, the specified cost of the heat transfer area, and the cost of utilities are taken to be the same as for the system without additional compression. The estimated payback period of the system's retrofit project with the additional compression of the ammonia stream will amount 7 months.

CONCLUSIONS

An analysis of the operation of a supermarket ammonia refrigeration cycle shows the possibility of using the overheating and condensation heat of the ammonia stream. This heat may be used to heat water and air, thus considerably reducing the expenditures on utilities. The additional compression of the ammonia stream improves heat integration, but the implementation of this project requires great capital investments. However, the economic estimation of this retrofit project shows its reasonability. This methodology can be used to determine the capital costs of heat exchange networks within large industrial complexes that use intermediate utilities [21].

The results of our work can also be used to reconstruct existing supermarket ammonia refrigeration cycles and design new refrigeration cycles. When implementing these projects, it is necessary to perform an additional analysis of energy consumption systems, since each of them has its own set of streams, equipment features, and process constraints.

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NOTATION

CP—stream heat capacity, kW/K;
C_p—heat capacity at a constant pressure, kJ/(kg K);
G—mass flow rate, t/h;
ΔH—stream enthalpy, kW;
$Q_{C\min}$—minimum power of cold utilities, kW;
$Q_{H\min}$—minimum power of hot utilities, kW;
Q_{Rec}—heat recovery, kW;

r—latent phase transition heat, kJ/kg;
t—temperature, °C;
t_S—supply temperature, °C;
t_T—target temperature, °C;
Δt—temperature difference, °C;
$\Delta t_{\min}$—minimum temperature difference, °C;
Π—reduced cost, USD.

SUBSCRIPTS AND SUPERSCRIPTS

Cmin —minimum power of cold utilities;
Hmin —minimum power of hot utilities;
min—minimum;
Rec—heat recovery;
S—supply temperature;
T—target temperature.

REFERENCES

1. Klemeš, J. and Perry, S.J., Process Optimization to Minimize Energy Use in Food Processing, in *Handbook of Waste Management and Co-Product Recovery in Food Processing*, Cambridge: Woodhead, 2007, vol. 1, p. 59.
2. Klemeš, J.J., Varbanov, P.S., and Pierucci, S., Process Sustainability and Operability via Integration, Energy Saving and Pollution Reduction, *Theor. Found. Chem. Eng.*, 2012, vol. 46, no. 6, p. 1.
3. Klemeš, J., Friedler, F., Bulatov, I., and Varbanov, P., Sustainability in the Process Industry, in *Integration and Optimization,* New York: McGraw-Hill, 2010.
4. Tovazhnyanskii, L.L., Kapustenko, P.A., Ul'ev, L.M., Boldyrev, S.A., Arsen'eva, O.P., and Tarnovskii, M.V., Thermal Process Integration in the AVDU A12/2 Crude Distillation Unit during Winter Operation, *Theor. Found. Chem. Eng.*, 2009, vol. 43, no. 6, p. 906.
5. Meshalkin, V.P. and Boyarinov, Yu.G., Semi-Markovian Models of the Functioning of Complex Chemical Engineering Systems, *Theor. Found. Chem. Eng.*, 2010, vol. 44, no. 2, p. 186.
6. Nemet, A., Varbanov, P., and Klemeš, J.J., Waste-to-Energy Technologies Performance Evaluation Techniques, *Chem. Eng. Trans.*, 2011, vol. 25, p. 513.
7. Reay, D.A. and Macmichael, D.B.A., *Heat Pumps: Design and Applications*, Oxford UK: Pergamon, 1988.
8. Gorshkov, V.G., Heat Pumps: An Analytical Review, *Spravochnik Promyshlennogo Oborudovaniya,* 2004, no. 2, p. 47.
9. Calm, J.M., Heat Pumps in the USA, *Int. J. Refrig.*, 1987, vol. 10, no. 4, p. 190.
10. Korfitsen, E. and Kristensen, A.P.R., Ammonia High Pressure Heat Pumps in Food Refrigeration Applications, *Int. J. Refrig.*, 1998, vol. 21, no. 3, p. 212.
11. Kemp, I.C., *Pinch Analysis and Process Integration: A User Guide on Process Integration for the Efficient Use of Energy*, Oxford: Butterworth, UK, 2007, 2nd ed.
12. Smith, R., *Chemical Process Design and Integration*, Chichester: Wiley, 2005.
13. Smit, R., Klemeš, I., Tovazhnyanskii, L.L., Kapustenko, P.A., Ulyev, L.M., *Osnovy integratsii teplovykh protsessov* (Principles of Thermal Process Integration), Kharkov, Ukraine: KhPI, 2000.
14. Becker, H. and Marechal, F., Targeting Industrial Heat Pump Integration in Multi-Period Problems, *Comput. Aided Chem. Eng.*, 2012, vol. 31, p. 415.
15. Klemeš, J.J. and Varbanov, P.S., Heat Integration Including Heat Exchangers, Combined Heat and Power, Heat Pumps, Separation Processes and Process Control, *Appl. Therm. Eng.*, 2012, vol. 43, p. 1.
16. Kapustenko, P.O., Ulyev, L.M., Boldyryev, S.A., and Garev, A.O., Integration of Heat Pump into the Heat Supply System of Cheese Production Plant, *Energy*, 2008, vol. 33, no. 6, p. 882.
17. Shcherbin, V.A., *Kholodil'nye stantsii i ustanovki* (Refrigerating Stations and Units), Moscow, Russian Federation: Khimiya, 1976.
18. UniSim Design Software. www.Ahpsweb.honeywell.com/Cultures/en-US/Products/ControlApplications/simulation/UniSimDesign/default.htm. accessed September 10, 2012.
19. ALFA LAVAL. www.alfalaval.com/Pages/default. aspx. accessed August 22, 2012.
20. Nemet, A., Klemeš, J.J., and Kravanja, Z., Minimization of a Heat Exchanger Networks' Cost over Its Entire Lifetime, *Energy*, 2012, vol. 33, no. 6, p. 882.
21. Nemet, A., Varbanov, P.S., Kapustenko, P., Boldyryev, S., Klemeš, J.J., Capital Cost Targeting of Total Site Heat Recovery, *Chem. Eng. Trans.*, 2012, vol. 29, p. 1447.