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ELECTROCHEMICAL HEAT PUMP for the "Helsinki Energy Challenge" project

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Abstract: *The article analyzes the promising options for replacing the Helsinki district heating system based on the combustion of fossil fuels in a thermal power plant and presents a choice of alternative heat supply systems that do not generate carbon dioxide and do not emit it into the atmosphere (heat supply systems based on heat pumps and electric heating based on boilers). In addition, a fundamentally new type of heat pump according to the patent of Ukraine No. 855584 is proposed in the heat cycle of which the electrochemical energy conversion mechanism (ECHP) is used, and which is able to compete with traditional compression type heat pumps.*

Keywords: *Helsinki heat supply system, coal burning, carbon dioxide generation, global warming, renewable energy, heat pump, electrochemical mechanism, fuel cell, electrolyzer.*

1. INTRODUCTION

In recent years, the planet's climate began to "warm up" quickly due to the accumulation in the atmosphere of carbon dioxide emissions accumulated during the industrial era, mainly due to human activities. An increase in the concentration of CO_2 in the atmosphere led to a worsening of the so-called greenhouse effect [1], which caused global warming. Climate warming threatens dangerous consequences for humanity, especially for its poorest part living in the tropics.

As part of the fight against global warming, the Helsinki City Hall set an ambitious goal: to transform the capital of Finland into a city of "zero emissions" of carbon dioxide until 2035 [telegram-channel "Killerwhale", 12/05/2019]. Achieving this goal, along with reducing CO_2 emissions from urban transport, involves replacing the existing heat supply system (HSS). This is one of the most important tasks of the city, since more than half of all CO_2 emissions in Helsinki are produced through the production of thermal energy necessary for heating in the cold part of the year.

Today, more than half of the thermal energy in Helsinki is produced at urban heat and power plants (CHP), which operate only on coal. In accordance with the plan of the Government of Finland until 2029, coal-fired power plants and thermal power plants throughout the country should be closed or reprofiled. Thus, the problem of achieving zero CO_2 emissions should be solved by switching to the generation of heat and electricity solely on the basis of renewable energy sources.

Currently, in Helsinki, a centralized HFS based on a CHPP has been implemented. In 2018, urban CHP plants generated 7,200 GW*hour of thermal energy, of which 3,850 GW*hour, or 56%, produced CHPs that operate on natural gas. According to the calculations of the Norwegian research organization **Sintef**, coal is the most "dirty" type of fossil fuel in terms of carbon dioxide emissions. In the production of 1 MW*hour of electricity, about 0.8 tons of CO_2 are emitted from coal, and in the production of 1 MW*hour from natural gas - 0.4 tons of CO_2.

The director of the **Helsinki Energy Challenge** project, L. Uuttu-Deshriver, said that the solution of the task of switching the city to a new type of STS (i.e., without CO_2 emissions) suggests that it will be based on generating electricity from renewable sources, and the implementation of this goal will require billions investment.

2. REVIEW

Centralized HSS is a heat supply network, including, on the one hand, a heat generator, which is an integral element of thermal power plants (which are usually located outside the city), and on the other hand, HSS includes a number of heat points located in the city area near individual heat consumers [2]. Thermal power stations and heating units are interconnected by heating mains, including a pair of thermally insulated pipes for supplying heated and discharged cooled coolant (deaerated water).

Centralized HSS of large objects are of two types. The first uses CHP plants that typically run on fossil fuels (coal, fuel oil or gas). In the case of using a thermal power plant, the low-pressure steam condenser is working fluid, which heats the coolant with condensation heat. But CHP is a source of large-scale generation of carbon dioxide emitted into the atmosphere. Moreover, the maximum CO_2 emissions

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per unit of heat generated occur when using coal [3]. The second type of centralized HSS is based on large heat pump units (HPU), which operate on electricity and use the heat of river or sea water as a source of heat of low potential. Moreover, this type of centralized HSS does not produce CO_2 emissions into the atmosphere.

It is also possible to use a centralized HSS as a heat generator of a geothermal source of thermal energy (a petrothermal type), which includes a number of very deep wells in overheated rock [4].

Decentralized heat supply systems are intended only to provide individual consumers. In decentralized HSS there are practically no heating pipelines, since their heat generators are usually installed directly in consumers' heating stations. In this case, either electric boilers or small heat pumps are used as heat generators. Small heat pumps are powered by electricity, and the following is used as a source of heat of low potential - either the heat of the surrounding air, or the heat of the soil through underground heat exchangers, for example, in the form of shallow wells.

3. STATEMENT OF THE PROBLEM

An analysis of HSS that do not have carbon dioxide generation for Helsinki heat supply leads to a choice of three most likely options:

1) The first option is a centralized HSS based on a new large heat pump units (HPU) at the site of a dismantled TPP using the existing workable heat distribution system for consumers (heating mains and heating stations).

2) Two versions of decentralized HSS (usually used only for individual consumers): the first option is based on small HPs and the second is based on electric boilers.

4. RESEARCH RESULTS

4.1. Analysis of probable HSS options

Obviously, the most inefficient option from those considered from the point of view of technical thermodynamics is decentralized HSS based on electric boilers, since it is well known that the efficiency of electric heating is much lower than the efficiency of heating based on HP. And the most thermodynamically effective of the considered options, obviously, is HSS based on HP.

Therefore, the number of compared options can be immediately reduced to two options based on HSS with HP. And when comparing these options, you can already take advantage of their economic efficiency. If we take into account that in the centralized HFS of Helsinki, on the basis of HPU, almost all elements of the existing infrastructure of the HFS of the city will be used (that is, its entire heating network, excluding the CHP), it is obvious that it will be much cheaper than a system of many separate HFS on basis of small HPs for individual consumers, in which each individual HP is equipped with its own low-potential heat source (for example, in the form of an installation for selecting the heat of atmospheric air or the heat of the soil [5].

4.2. The principle of operation of the heat pump

It is known [6] that in a direct thermodynamic cycle heat Q_1 is supplied to a heat engine from a source with a high temperature. As a result of its functioning, the heat engine generates useful energy W (mechanical or electrical) and releases the waste heat of the Q_2 cycle, which is removed to the environment. In accordance with the law of conservation of energy, $Q_1 = W + Q_2$; therefore, the energy conversion efficiency in the direct cycle is $\eta < 1$ ($\eta = W/Q_1 = 1 - Q_2/Q_1$). And in a heat pump that operates in the reverse thermodynamic cycle, the directions of heat and energy flows are reversed. The energy W in this case is not diverted, but is supplied to a heat engine, which thereby removes heat Q_2 from a heat source with a low temperature (usually from the environment) and brings it along with its work W to the heat transfer medium HSS. As a result, the heat generator generates a heat flux Q_1 ($Q_1 > Q_2$) and gives it out at heat points to the heat supply system of consumers. In contrast to the direct heat cycle, for the evaluation of the efficiency of which the concept of efficiency is used ($\eta = W/Q_1$), the concept of the heating coefficient is used to evaluate the efficiency of the reverse cycle of the heat pump: $\varepsilon = \eta^{-1} = Q_1/W = 1 + Q_2/W$ ($\varepsilon > 1$). Its value can be approximately estimated based on the analysis of the energy conversion efficiency in the reverse Carnot cycle, for which $\varepsilon = T_1/(T_1 - T_2) = 1 + T_2/\Delta T_{12}$, where T_1 is the absolute temperature of heat removal Q_1 from the heat source to the heat transfer medium HSS, T_2 Is the temperature (K) of heat removal Q_2 from a low-temperature source (i.e., the environment) to the working fluid HP ($T_2 \approx T_0$ is the temperature of river water or atmospheric air, K), and $\Delta T_{12} = (T_1 - T_2)$ is the temperature difference : removal of heat Q_1 from HP to the heat transfer medium HSS and supply of Q_2 to HP.

4.3 Types of heat pumps

The main type of HP, in which the reverse Rankine thermodynamic cycle is realized, is a compression heat pump. In it, the heat Q_2, taken from the environment, is added to the energy W, which is supplied to the compressor.

The second most common is an absorption type heat pump. By the way, in the recent past, adsorption refrigerators were widely used in everyday life. These refrigerators were characterized by very high reliability, but low efficiency.

The third is a thermoelectric heat pump based on the Peltier and Seebeck effects. Of all the types considered, it has the lowest thermodynamic efficiency and is used only in special cases.

There are other types of heat engines that implement the reverse heat cycle (for example, gas refrigeration cycle, steam jet cycle, etc.), but they are not used as heat pumps.

4.4. Heat pump according to patent UA No. 85584

A fundamentally new method of energy conversion according to the patent of Ukraine No. 85584 (heat pump cycle [7]) makes it possible to carry out quasi-reversible conversion of electric energy into low-grade heat for the needs of heat supply as part of an electrochemical mechanism. The electrochemical heat pump includes an electrolyzer (which decomposes water into H_2 and O_2 gases under normal conditions) and a fuel cell [8], in which H_2O is synthesized from these gases at 100 °C in the form of saturated steam. This steam turns into a liquid in the condenser, and the corresponding heat of the phase transition heats the heat carrier in it from the heat supply system. The electric energy necessary for electrolysis of water is supplied from the fuel cell and, additionally, from an external source (for example, the power grid). In this case, the heat for heating the coolant of the heat supply system significantly (several times) exceeds the additional share of electricity from an external energy source due to the replacement of the thermal effect of the endothermic electrode reaction of water decomposition into gases by heat from the environment (for example, heat taken from the river water).

Already the first theoretical evaluations of the energy conversion efficiency showed that the electrochemical heat pump cycle, implemented between temperatures of 25 °C and 100 °C, has a heating coefficient ε of about 4.7 (ideally, the reverse Carnot cycle under these conditions will provide only 6% higher - 5.0). It is important that more than 70% of the heat released in the fuel cell as a result of an exothermic electrode reaction at a temperature of 100 °C will be transferred to the heat carrier from the heat supply system due to condensation of saturated steam of the working fluid.

4.5. Electrochemical heat pump circuit description

The method of converting electricity to heat according to UA patent No. 85584 is implemented as part of an electrochemical heat pump, a diagram of which is shown in Fig. 1.

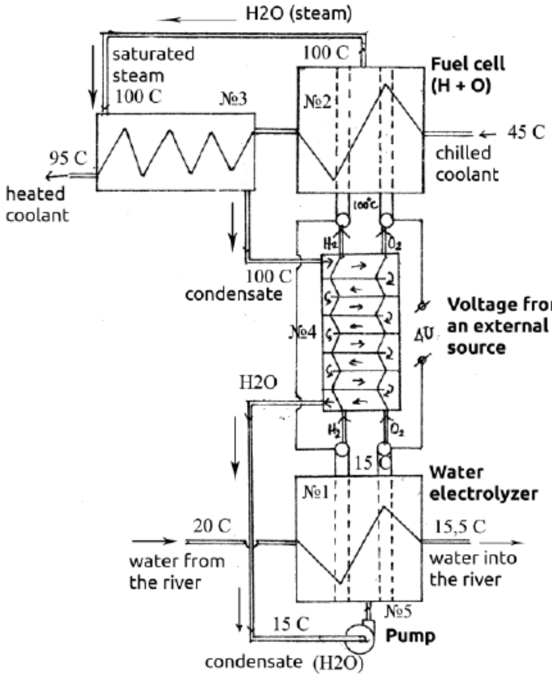

Fig 1 - Scheme of the electrochemical heat pump in HSS

The electrochemical heat pump (see Fig. 1) includes a low-temperature water electrolyzer 1 (EL), which decomposes it into H_2 and O_2 gases and fuel cell 2 (FC), which synthesizes H_2O in the form of saturated steam at elevated temperatures (more than 60 °C), saturated steam heat exchanger-condenser 3, heat exchanger 4 for heat recovery in the cycle and electric pump 5 for supplying water from condenser 3 to EL 1.

The ECHP heat pump operates as follows: voltage is supplied from an external DC source to the electric circuit of the EL 1 and FC 2 connected in series, as well as to the pump 5. EL 1 decomposes the water that is supplied by the pump 5 into H_2 and O_2 gases with absorption of the thermal effect electrode reaction Q_{end} from the environment (more precisely, from a tubular coil in EL 1 through which, for example, water from a river is pumped at +20 °C). The H_2 and O_2 gases obtained in EL 1 at 20 °C are supplied to the corresponding coils of the countercurrent heat exchanger 4 of the heat recovery cycle, in which the condensate of water vapor gives off heat from the gases (from 100 ° to 20 °C). The H_2 and O_2 gases heated to 100 °C are then supplied from the heat exchanger 5 to FC 2, where they undergo a recombination reaction with the formation of H_2O in the form of saturated steam at 100 °C and the thermal effect of the electrode reaction Q_{ekz} is released in FC 2. This heat is supplied to the heat carrier, which flows in a tubular coil installed in FC 2. The heat carrier of the heating system, preheated in FC 2 due to Q_{ekz}, is supplied to the steam heat exchanger-condenser, where it is heated to a predetermined temperature by the phase transition heat released during condensation of saturated steam synthesized in FC 2 at a pressure of 1 bar. and a temperature of 100 °C, and then diverted to heating appliances. The resulting condensate is fed to a counterflow heat exchanger 4 for its subsequent cooling as part of the heat recovery in the cycle.

Consider the case of complete reversibility of the processes in EL 1 and FC 2 at a pressure of 1 atm. The process of electrolytic decomposition of water in EL 1 at an ambient temperature of +20 °C (for example, river water flowing through a coil) will be implemented at + 15 °C (this will compensate for the thermal effect of the electrode reaction Q_{end} in EL 1 due to the heat of the environment). EL 1 for operation under these conditions will consume electricity at voltage ~1.23 V.

The reaction-recombination of H_2 and O_2 gases in the process of ECG, which is realized at a temperature of 100 °C to obtain H_2O in the form of saturated steam, will ensure the generation of electricity in the FC 2 at a voltage of 1.162 V with the release of the thermal effect of the electrode reaction Q_{ekz}, which is removed from the FC 2 by the coolant from the heating system ("return"), which receives pre-heating in the coil. To a predetermined temperature, the coolant is then heated in the heat exchanger-condenser 4 due to the heat of condensation of saturated steam (10.5 kcal/mol) coming from the fuel cell 2, and is supplied to the heating system (the coolant at 100 °C is "hot water"). FC 2 at 20 °C outputs 1.23 V to the terminals when receiving H_2O in the form of water and 1.18 V when receiving H_2O in the form of steam. The difference of 0.05 volts is due precisely to the condensation heat of 10.5 kcal/mol. At a temperature of 100 °C with the removal of H_2O in the form of steam, the FC 2 generates a voltage (1.162 V) to the terminals, which is also 0.05 Volts lower than in a FC with obtaining water at 100 °C. Thus, an external source of electricity supplies a voltage of 0.068 V to the cycle, of which only 0.05 Volts is spent on the reversible conversion of water into steam in the thermodynamic cycle of an electrochemical heat pump.

4.6. Problems of switching to heat pumps

Modern heat pumps are based on the compression thermodynamic cycle (on the reverse Rankine cycle), they have a number of significant drawbacks: large irreversible losses during expansion of the working fluid vapor by throttling on the washer, significant mechanical losses in the compressor and its high noise level. The electrochemical heat pump is better than the well-known analogue (compression type HP) in a number of parameters, because it is: more efficient and reliable, almost silent and very compact. Compression heat pumps are designed for use in low-temperature heat supply systems (heating and domestic hot water). The thermophysical properties of the known working fluids do not allow single-stage compression heat pumps to heat the coolant in the heat points of the existing heat supply systems to 75 °C, and even more so to 100 °C. And two-stage heat pumps that can do this are very complex and too expensive. Electrochemical heat pumps [9] will provide the needs of existing heating systems with a coolant with a temperature of about 100 °C, which does not require their conversion to a low-temperature coolant (by significantly increasing the surfaces of heating devices and coolant flow). The proposed method of operation of the heat pump according to the patent of Ukraine No. 85584 creates a unique opportunity to solve the problem of switching to a new heat supply technology based on highly efficient electrochemical equipment (water electrolyzers and fuel cells).

4.7. Calculation of theoretical energy conversion efficiency in a heat pump

The energy conversion efficiency in the reverse cycle of the heat pump for ECHP is determined by the value of the heating coefficient $\varepsilon = Q_{FC}(T_1)/\Delta G_{HP}$, where Q_{FC} is the thermal effect of the exothermic electrode reaction in the fuel cell, $\Delta G_{HP} = G_{EL} - G_{FC}$, where G_{FC} is free energy (energy Gibbs [10]), which is converted into electricity in a fuel cell, G_{EL} – Gibbs energy, which is converted into the chemical energy of hydrogen and oxygen in an electrolyzer. Gibbs energy G_{EL} of the electrode reaction in the electrolyzer at **n.o.** it is equal to 113.4 kcal/mol (U = 1.23 V), and G_{HP} (for 100 °C) = 107.1 kcal/mol (U = 1.162 V). Since the enthalpy of reaction H(100 °C) ≅ H(25 °C) = 136.5 kcal/mol, the thermal effect of the electrode reaction in the fuel cell $Q_{FC} = H - G_{FC} = 136.5 - 107.1 = 29.4$ kcal/mol. Thus, the theoretical value of the heating coefficient of the electrochemical heat pump $\varepsilon = Q_{FC}(T_1)/\Delta G_{HP} = 29.4/(113.4 - 107.1) = 4.69$, which is only 6% lower than in the reverse Carnot cycle ($\varepsilon_k = 5.0$). Moreover, more than 70% of the heat that is released in the fuel cell as a result of an exothermic electrode reaction at a temperature of 100 °C will be transferred to the heat carrier from the heat supply system due to condensation of saturated steam.

4.8. The results of research cycles and development of the layout ECHP.

Patent of Ukraine No. 85584 for the "Method of reversible conversion of electricity into heat" (ECHP) was issued in early 2009, and in September 2010 the Ministry of Education and Science of Ukraine allocated funding for a theoretical analysis of the effectiveness of electrochemical thermal cycles [7, 11] and the development of a layout ECHP. A year and a half in the framework of the NIS NTUU "KPI" studies were conducted on this topic (NTUU "KPI" together with the Institute of NASU "IBONH"), and the author of Patent No. 85584 was entrusted with these studies. According to the first stage of research, on December 29, 2011, the author of the patent published an interim report on the scientific topic d/w 2218f "Energy of Hydrogen" (57 pages). As a result of scientific research, theoretical studies were performed and an ECHP model was made (in accordance with the statement of work), the test of which showed that a hydrogen-oxygen fuel cell using a «nafion» type TEM at 100 °C is fully operational and H_2O is removed from it in the form of saturated steam. But it turned out that electrolysis of water under normal conditions "slows down", since distilled water is a very weak electrolyte. Therefore, at the first stage, we had to use the WODEN-1 hydrogen source as an electrolytic cell, and problems with the generation of O_2 appeared that were planned to be solved at the second stage of the research. But at the beginning of 2012, the scientific topic d/w 2218f was closed due to the cessation of funding.

5. CONCLUSIONS

The analysis showed that the most acceptable option for the new Helsinki HSS from both economic and thermodynamic points of view is a centralized HFS, which will use the existing infrastructure of urban heating networks, but with a new heat generator in the form of a large heat pump with the extraction of heat Q_2 from the environment - by cooling river or sea water.

The economic efficiency of generating electricity from renewable energy sources to ensure the operation of HPI, declared by the project director, will be very low. It is much cheaper for this purpose to use the electricity received at nuclear power plants without CO_2 emissions, for example, at first due to imports from neighboring Russia, until the Finnish Olkiluoto-3 nuclear power plant is put into operation.

Also in the article, as an alternative to the existing compression type HPs, a fundamentally new type of HPs (ECHPs) is proposed, which operates on the basis of an electrochemical mechanism and which can provide worthy competition for compression type HPs in the case of solving problems encountered during research on the scientific topic "Hydrogen Energy ".

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