

Innovative model of trigeneration system generating desalinated water, hot and cold by using low grade heat recovery from nuclear reactor set in cascade of sorption devices

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Abstract. The paper introduces an innovative conceptual model of a trigeneration system based on implementation of sorption devices in cascade configuration: absorption heat pumps and adsorption chillers connected with thermal energy storage, for recovering useless heat from secondary cooling circuit of a research nuclear reactor. Proposed trigeneration source provides building with useful heat for the purposes of heating system with thermal energy storage and cold for air-conditioning purposes. Also, desalinated water covering technological demand is produced. Useful heat is produced by an absorption heat pump, cold and desalinated water by adsorption chiller/desalinator. For the described trigeneration system calculations based on commercially available equipment (lithium-bromate absorption heat pumps and silica-gel adsorption chillers with desalination option) and required heat/cold/desalinate demand have been carried out. Operational data collected from an existing installation extended by introducing thermal energy storage to the system was used to simulate the heat demand during the year. 5-year operational data from the “MARIA” research nuclear reactor located at the National Center for Nuclear Research in Świerk, Poland was used to simulate low source variations for the absorption heat pump operation. The results of model implementation demonstrate a series of promising effects on many levels of system operation, including production of desalinated water on a large scale and significant reduction of: (I) energy usage (by 40% when considering only heating scenario), (II) nuclear fuel consumption, (III) heat delivery losses.

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1 Introduction

Conventional primary energy resources are finite and known methods of use impact the environment. Technologies for the production of renewable energy using wind or sun are facing technical problems associated with the availability of power during periods of high demand. This leads to a detailed analysis of primary energy losses in conventional systems and the use of technologies for recycling waste energy (with parameters preventing direct use) or useless (with parameters allowing direct use, but not available at the time of demand) and the revision of assumptions related to optimal system configurations. The rate of improvement in energy efficiency is falling, showing that simple modifications have been implemented and it's time for more advanced solutions. Substantial potential lies especially in low-grade heat sources treated as waste heat. Energy-intensive industry is responsible for 69% of global primary energy consumption in industry [1] and 45% of CO₂ emissions into the atmosphere. Most of this energy is used to produce electricity and heat [2], of which almost 17%, at a temperature not exceeding 120°C [3], is discharged directly into the atmosphere. Dry coolers and cooling towers are mainly used for this purpose, generating additional costs and energy consumption. Implementation of the technology to convert waste and useless heat to useful energy could lead to a global reduction of CO₂ emissions into the atmosphere by 7–12% [4]. When considering heat sources available for recovery, nuclear reactors circuits should be considered as well. For example, in light water nuclear reactors, low temperature heat can be retrieved in two forms: as bleed steam from a low pressure steam turbine or warm water, either from the condenser cooling loop (indirect cooling) or taken from the discharge to the infinite heat sink, such as a lake or major river (direct cooling). In the first case the temperature ranges from 200°C to 70°C. In the second case the temperature is below 40°C. The first area of heat recovery, due to the relatively high temperature, is already utilized – the heat is commonly used to preheat the feedwater in a cascade set of heat exchangers. Sometimes it is used for district heating (e.g. Nogent-sur-Seine Nuclear Power Plant [5]). There are also cases of using this heat in the desalination of feed water (e.g. Takahama Nuclear Power Plant) and drinking water desalination is considered [6]. A highly problematic waste heat source, due to its low temperature and high impact on reactor operation, is water from the condenser cooling loop or from the discharge to the infinite heat sink. This heat source, if the temperature could be upgraded, could be used in District Heating Systems or industrial applications directly. When waste or useless heat recovery and recycling is considered, correlation of production and demand should be analyzed. For example, in Local Heating Cooling Systems (LHCS) there are significant fluctuations in consumer demand for heat during both the heating and the summer seasons. During the heating season the fluctuations are associated with rapid changes in meteorological conditions, such as outside air temperature, solar radiation and wind speed. During the summer season the fluctuations are also associated with changes in outside air temperature, solar radiation and variable demand for domestic hot water. These variations in the consumer demand for heat cause significant problems in operational terms, forcing frequent changes to energy generating units' heat power, which in turn lead to a reduction in the efficiency of heat generation and in the security of heat delivery to heat and cold consumers. Introducing additional thermal capacity to the LHCS in the form of Thermal Energy Storage (TES) would be highly recommended on these grounds alone. Also, application of TES system in this LHCS ensures heat delivery to heat and cold consumers in case of stopping in operation of the research nuclear reactor for some period of time, what frequently happen. Paper introduces novel conceptual layout and calculations of Absorption Heat Pump (AHP) system recovering waste heat from secondary cooling circuit of nuclear reactor and producing useful heat for purposes of heating and cooling.

1.1 Absorption Heat Pumps

The idea behind AHP technology is the harnessing of heat in a non-usable form (called Low Source – LS) and with steam, hot water at a temperature above 100°C or direct burning of fuel used as supply energy (called High Source – HS) converting it into a usable temperature heat (typically ~95°C). Lithium Bromide – Water (LiBr – H₂O) is the most common working pair in the system. The LiBr aqueous solution used in AHP is salt, considered to be a non-hazardous medium. Water as a refrigerant is the most environmentally friendly refrigerant available. The working principles of the AHP are as follows: In a generator, by means of heat supplied for example in the form of steam, hot water or directly from a burner supplied with any type of fuel, water evaporates from diluted LiBr-H₂O solution. Evaporation in the generator is possible due to the pressure being significantly lower than atmospheric pressure. Evaporated clean water vapor travels to the condenser and, when condensed, releases heat through an indirect heat exchanger. Water liquid obtained in this way is passed to the evaporator, where while evaporating on the indirect exchanger in the conditions of high vacuum, it collects non-usable heat from the low source. During this process refrigerant liquid water evaporates. Refrigerant vapor produced in the evaporator is then absorbed in the absorber by a concentrated LiBr solution from which, earlier, water in the generator was evaporated – maintaining a high vacuum in the AHP and a low boiling temperature in the evaporator. The absorption process is strongly exothermic, thus the receipt of a significant quantity of heat by the indirect exchanger is also required, which constitutes an additional source of energy and the first degree of heating of the inlet hot water returning, e.g. from a district heating system. During absorption of refrigerant vapor, the concentrated solution is diluted and transferred by the solution pump back to the generator where the water from the solution evaporates again and the cycle continues. Proper operation of AHP requires, above all, the heat in two forms – steam, hot water or burnt fuel for the generator (High Source) and low-temperature heat for the evaporator (Low Source). Electric supply of the AHP control system and circuit pumps of approximately 0.1% of the AHP heating capacity is also necessary. Fig. 1 presents a diagram of a commercially available absorption heat pump device.

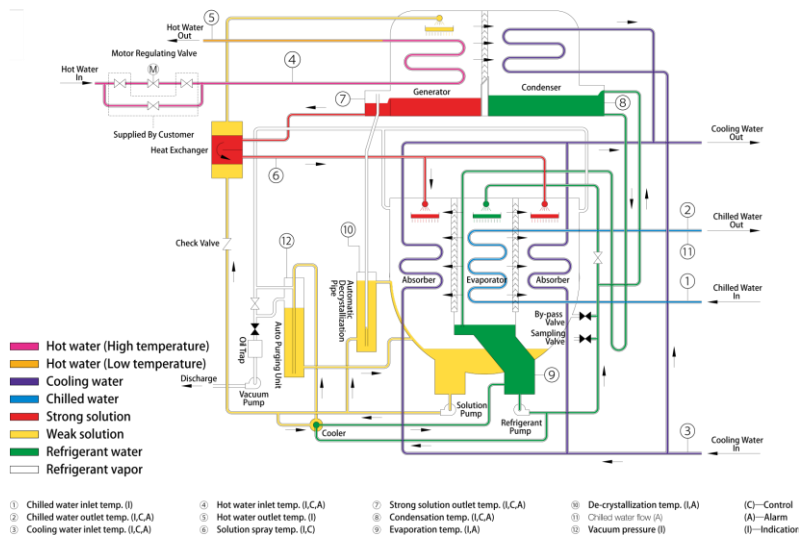


Fig. 1. Absorption Heat Pump diagram (Li-Br type).

1.2 Adsorption chillers

Sorption technology has been a well-known cooling technology for decades. The most popular types of sorption cooling devices are LiBr absorption chillers enabling utilization of high temperature waste heat (water, steam or flue gas) or production of cooling capacity almost without using any electricity (burner type). LiBr chillers enable efficient production of chilled water with Coefficient of Performance (COP) of 0.8 (single effect), 1.4 (double effect) or even 1.7 (triple effect). Unfortunately, commercially available solutions are unable to produce chilled water when supplied with low grade heat (temperature < 70°C). In recent years three bed adsorption cooling and desalination technology has been commercialized, enabling efficient (COP > 0.7) production of chilled water when supplied with low grade heat (temperature < 70°C). The working principle of adsorption chillers is similar to absorption chillers and heat pumps: sorption and desorption of the same refrigerant – water – not from aqueous Li-Br solution but using solid silica gel. The main component of an adsorption chiller consists of beds filled with silica gel – a sorbent with very high water adsorption capacity. If the beds are cooled with cooling water the silica gel refrigerant adsorption capacity increases, maintaining very low pressure in the evaporator thus producing effective cooling capacity. When the bed reaches maximum adsorption capacity it has to be isolated from the evaporator, connected to the condenser and heated with hot water to desorb the refrigerant. Refrigerant vapor is condensed and used in the evaporator to produce cooling capacity. Each bed can be at the same time in the adsorption, desorption or regeneration stage, thus the use of three beds guarantees constant heating demand and chilled water production. Adsorption chillers, in addition to efficient cooling capacity production when supplied with warm water, also have another advantage – if the evaporator is supplied with brackish / sea water pure water is evaporated and can be discharged from the condenser as distillate. The scope of use of adsorption chillers for desalination purposes is growing intensively due to the low operational costs of such systems. Fig. 2 presents a diagram of a commercially available three bed adsorption chiller and desalination device.

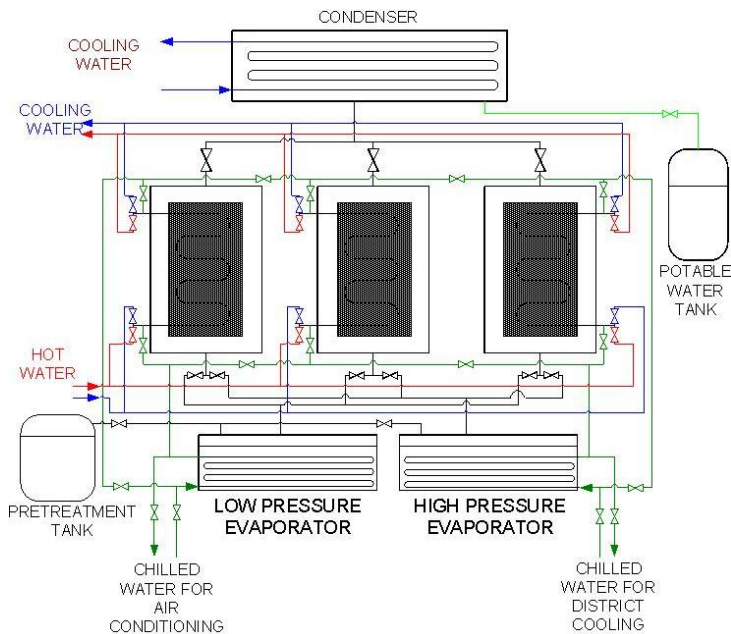


Fig. 2. Adsorption chiller with desalination option (3-bed type).

1.3 Thermal Energy Storage

Heat storage in water, thermally stratified TES is one of the easiest ways to collect thermal energy [7]. The TES is a tank that stores thermal energy in the form of hot water. In TES hot water collects in the top part of the tank and is separated by a relatively narrow thermocline from cold water at the bottom of the TES tank, Fig. 3. The height of this type of tank can be as much as tens of meters, and their capacity reaches tens of thousands of cubic meters. When charging the TES, hot water from boilers (or heat exchangers) pushes the cold water towards the bottom of the tank, which then flows into the boilers. When discharging the TES, return water from LHCS called “cold water” displaces the hot water towards the top of the tank and then to the supply pipeline of the LHCS. The water level in the TES tank remains practically unchanged, only the amount of hot and cold water in the tank changes, as does the location of the thermocline. In order to avoid oxygen penetrating from the ambient air to the hot water stored in the TES tank, a steam bed is applied above the water in the tank [8].

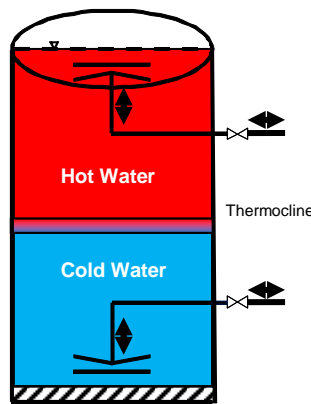


Fig. 3. Operating principle the water, thermally stratified TES.

To select the best TES system for a particular LHCS, it is necessary to collect and analyze operational data for the heat source and for the entire LHCS (temperature, pressure, water flows, weather conditions, etc.). The analysis should cover at least the last 2–5 years, to establish the trends and to confirm the existing forecasts regarding future operation of the LHCS.

2 Introduced model

2.1 Model preparation

To assess the environmental and energy impact of implementing an absorption heat pump with adsorption chiller for heating, cooling and desalination purposes in respect of nuclear reactor buildings using nuclear reactor secondary cooling circuit waste heat as a low source, conceptual and calculation model was introduced. Whenever possible, operating data has been used. If real data was not available, data from a similar structure was prepared. The model constituted of two parts – production and demand side. Key factor defining available capacity and maximum heat/cold production was low source temperature and availability. In this area historical operational data from the last five years (2012–2016) was used to prepare the model year which was the average of the whole period. Based on this data and maximum building heating demand validated by heat losses calculation compared with capacity

installed in oil boilers and their fuel usage an absorption heat pump was selected. Due to the lack of a cooling installation in the building heat gains were calculated and a cooling demand curve introduced to the model. Calculated heating demand was 930 kW of installed capacity and an average of 2978 GJ yearly energy usage. Predicted cooling demand was 226 kW of installed capacity and an average of 629 GJ yearly energy usage. A ratio of ~5 when considering heating demand to cooling demand is typical for air conditioning equipment operated only for summer months in the Polish climate. A system work algorithm was designed typically – heat is produced during the winter months for heating and domestic hot water production and in the summer months for domestic hot water and adsorption chiller needs. Table 1 indicates the selected low source temperatures and capacity available from the absorption heat pump. Due to low source temperature changes AHP was selected to cover heating capacity even during the coldest days, thus additional heating capacity is available when the low source temperature is higher.

Table 1. Low source and useful heat temperatures for selected absorption heat pump (T – Temperature, HW – Hot Water, LS – Low Source, AHP – Absorption Heat Pump).

	T in [°C]	HW in [°C]	HW out [°C]	LS out [°C]	AHP capacity [kW]
January	23.48	40	80	18.48	930
February	24.10	40	80	19.1	946
March	25.29	40	80	20.29	976
April	26.44	60	70	21.44	632
May	27.56	60	70	22.56	650
June	28.42	60	70	23.42	661
July	29.69	60	70	24.69	680
August	28.63	60	70	23.63	664
September	26.45	60	70	21.45	632
October	24.51	40	80	21.45	956
November	23.74	40	80	23.74	936
December	24.00	40	80	19	943

A simulation of the absorption heat pump and adsorption chiller was prepared based on commercially available equipment selection data and working curves defining key operational values such as efficiency, capacity and others. Due to the intermittent character of reactor work TES was introduced to the model. The calculation results of the required capacity of the TES tank for the analyzed LHCS indicate that the tank should have a volume of approximately 650 m³. The calculated volume makes it possible to compensate fluctuations in consumer demand for heat during both the heating and the summer seasons, and ensures heat delivery to heat and cold consumers in the case of the research nuclear reactor stopping operation for a period of time. The calculated volume of the TES tank should take into account the share of the non-useful space of the tank and its efficiency. Finally, the total volume of the TES tank for analyzed LHCS shall be on the level: $V_{TES} \cong 800 \text{ m}^3$

2.2 Model operation

The model is used to calculate the predicted heat for heating, cooling and desalination water production demand and to produce a comparison with existing oil boiler set energy usage. The first visible difference is a significant increase in heat demand during summer time due to the adsorption chiller for cooling and desalinated water operation. When only heating (space heating and domestic hot water) is considered 2978 GJ are needed. When heat demand for cooling and desalination is added (respectively 899 GJ and 1722 GJ) total heat demand

reaches 5599 GJ, of which more than 2200 GJ comes from waste heat recovered from the secondary cooling circuit of the MARIA nuclear reactor. Fig. 4 presents a diagram of heat demand for heating and cooling during the model year.

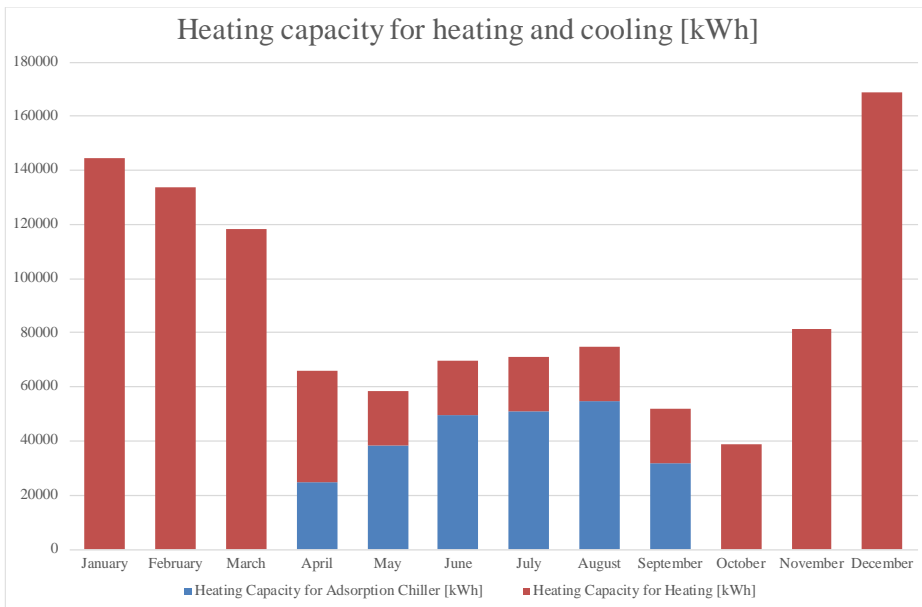


Fig. 4. Heat demand for heating and cooling.

An additional effect of model operation is the calculation of possible desalinated water production. The model implies that when an office building is not air-conditioned adsorption chiller capacity can be used for desalinated water production, allowing 536 t of distillate production during the model year. Desalinated water can be used for drinking or technological purposes. The final effect of model operation is to produce a comparison of energy usage from an existing oil boiler system with installed AHP with TES. In this area heating demand for non-existing installations (cooling and desalination) was neglected. When analyzing the model year for the existing system, yearly consumption of 91 360 l of oil would be necessary. When analyzing AHP with TES system, yearly consumption of 50 068 Nm³ of gas would be required. Due to ~40% of useful heat being recovered by AHP even adding fuel usage for cooling (in total 65183 Nm³ of gas would be consumed) keeps primary energy consumption at below the existing system.

3 Impact

The impact of implementing the AHP + TES system is visible on several levels. The simplest visible impact is a decrease in primary energy usage (from 91 360 l/a of oil to 50 068 Nm³ of gas) with a related decrease in atmospheric emissions. This effect is possible due to the recovery of 40% of the useful heat from the waste heat of the MARIA nuclear reactor. An additional important impact is the decreasing of the cooling water temperature in the reactor’s cooling circuit. Every nuclear reactor operates in critical mode, which means that each generation of fission born neutrons is the same as the last. In consequence, at every moment there is the same number of fission reactions and the power of the core is stable. Departure from this criticality is expressed as reactivity. This is controlled in MARIA by

control rods which may be raised or lowered to increase or decrease core reactivity. When fuel burns up, the reactivity of the core is decreasing and the control rods need to be raised. Therefore, to ensure operation of the core for several days, it is necessary to start the reactor with sufficient excess reactivity. Another parameter which influences core reactivity is the temperature reactivity coefficient. When cooling water heats up, it reduces in density and in consequences in neutron moderation ability. This plays an important role in the safety of the core, as in the case of an uncontrolled jump in heat generation, water reduces core reactivity and finally leads to a subcritical state of the core and reduces its power. Lowering the temperature of the water in the cooling system delivers additional excess reactivity to the core and allows the reactor to operate at higher efficiency. It is possible then to burn up fuel elements to a higher level. The temperature coefficient of the water inside fuel elements in the MARIA reactor is measured at $-1.8 \pm 0.3 \text{ } \mu/\text{ }^\circ\text{C}$ [9]. After the reactor starts operation the temperature changes typically from around 20°C up to 70°C depending on the fuel element [10]. Therefore, lowering the temperature in the secondary cooling circuit is desirable in reactor operation, especially during the summer heat when the efficiency of the cooling towers is insufficient. In such a situation it is necessary to decrease core power and in consequence decrease neutron fluxes in the irradiation channels. This has negative financial consequences in settlements with contractors [11]. The presented impacts fully justify future model development and demonstration implementation of the AHP + TES system in the MARIA research nuclear reactor.

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