Exergy analysis of a system using a chemical heat pump to link a supercritical water-cooled nuclear reactor and a thermochemical water splitting cycle

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Abstract

Increases in the power generation efficiency of nuclear plants are mainly limited by the permissible temperatures in nuclear reactors and the corresponding temperatures and pressures of the coolants. Coolant parameters are limited by the corrosion rates of materials and nuclear-reactor safety constraints. The advanced construction materials for the next generation of CANDU reactors, which employ supercritical water/steam as a coolant and heat carrier, permit improved operating parameters (outlet temperatures up to 625°C and pressures of about 25 MPa). An increase in the temperature of supercritical water allows it to be utilized in thermochemical water decomposition cycles to produce hydrogen. These methods are considered by many to be among the most efficient ways to produce hydrogen from water and to have advantages over traditional low-temperature water electrolysis. However, even lower temperature water splitting cycles (Cu-Cl, UT-3, etc.) require a heat supply at temperatures higher than 550-600°C. A sufficient increase in the outlet water/steam temperature from the nuclear reactor for a thermochemical water splitting cycle, without jeopardizing nuclear reactor safety, might be effectively achieved with a heat pump, which increases the temperature of the steam.

A high-temperature chemical heat pump, which employs the reversible catalytic methane conversion reaction is proposed. The reaction shift from exothermic to endothermic and back is achieved by changing the steam concentration in the reaction mixture. This heat pump, coupled with the second steam cycle of a supercritical water (SCW) nuclear power plant on one side and a thermochemical water splitting cycle on the other, increases the temperature of the "nuclear" superheated steam and, consequently, the quality of heat transfer into the water splitting cycle.

A comparative preliminary thermodynamic analysis is conducted of the combined system comprising a SCW nuclear power plant and a chemical heat pump, which provides high-temperature heat to a thermochemical water splitting cycle for hydrogen production. It is concluded that the proposed chemical heat pump permits the utilization efficiency of nuclear energy to be improved by at least by 2% without jeopardizing nuclear reactor safety. The influence of the steam/methane ratio in the heat pump working medium on the efficiency of the pump is investigated. Based on this analysis, further research appears to be merited on the proposed design of a nuclear power generation plant combined with a chemical heat pump, and implementation in appropriate applications seems worthwhile.

Keywords: Nuclear energy, supercritical water, exergy, chemical heat pump, hydrogen, thermodynamics.

1. Introduction

One of today's greatest technical challenges is to find a way to replace fossil fuels so as to significantly reduce greenhouse gas and pollutant emissions, and resolve concerns about global warming. One way to accomplish this is to generate electricity from renewable energy sources like wind, solar, tidal, geothermal, etc., and to produce hydrogen via water electrolysis for certain energy applications. The hydrogen can be utilized directly as a fuel or as a feedstock for producing synthetic liquid fuels. The significant quantities of expensive construction materials in renewable power plants often lead to higher electricity costs than for natural gas or coal power plants. Life cycle assessments of renewable technologies for producing electricity and hydrogen and reasons for the higher costs associated with renewable-based electricity and hydrogen have been considered by authors [1,2]. Given the current state of renewable technologies, many argue that the only viable alternative to fossil fuels is nuclear energy, even though it raises concerns with many. Nuclear energy must be used safely and effectively to produce power.

The efficiency of power generation normally increases with increasing temperature of the working medium which, in the case of the nuclear energy utilization, leads to increased nuclear-reactor coolant temperatures and pressures. Such increases in working-medium conditions are constrained by the characteristics and corrosion rates of construction materials and concerns about nuclear reactor safety. The advanced construction materials expected to be used in the next generation of CANDU reactors, which employ supercritical water/steam as a coolant and heat carrier, permit increased operating parameters (i.e., an outlet temperature up to 625^{o}C and a pressure of about 25 MPa). For the first generation of supercritical water (SCW) nuclear power plants, this is expected to increase the power generation efficiency from 35 to 45% [3]. Increasing the superheated steam temperature also makes it utilizable in thermochemical water splitting cycles to produce hydrogen. However, even lower temperature water splitting cycles (Cu-Cl, UT-3, etc.) often require heat at temperatures of 550-600°C or higher [4,5].

A sufficient increase in the outlet temperature of supercritical water/steam from the nuclear reactor to a thermochemical water splitting cycle, without jeopardizing nuclear reactor safety, might be achieved by application of a heat pump, which increases the temperature of the heat supplied via a cyclic process driven by mechanical or electrical work. The development of high-temperature heat pumps and their applications in high-temperature nuclear reactors is a substantially new area in engineering. Safonov et al. [6] proposed a high-temperature continuously-operated chemical heat pump connected to a gas-cooled nuclear reactor, where a shift from heat absorption to heat release was achieved by a pressure drop in the gaseous reaction mixture. Kato et al. [7,8] investigated a chemical heat pump that uses the reaction system of calcium oxide/lead oxide/carbon dioxide, which was developed for use on high-temperature heat (above 800^{0}C). The heat transfer from lower (about 800^{0}C) to higher (about 900^{o}C) temperature proceeds periodically through the heat storage and heat output modes. The same periodic characteristic is a feature of other chemical heat pump designs [9].

In this paper, a chemical heat pump is proposed and investigated that works continuously, absorbing heat at temperatures lower than 873 K (600^{o}C) and releasing it at higher than 873 K (600^{o}C). These parameters facilitate implementation of the heat pump in proposed designs for SCW-CANDU nuclear power plants. The transferred heat is appropriate for use in a chemical water splitting cycle to produce hydrogen. The purpose of this preliminary thermodynamic study is to evaluate the influence of introducing the proposed heat pump on the nuclear power generation plant efficiency.

2. Integration of a chemical heat pump into a SCW-CANDU power generation cycle

It is proposed to integrate a chemical heat pump into a SCW-CANDU power cycle.

2.1 Chemical heat pump

The operating principles of the proposed heat pump and its performance are described below. At higher temperatures, the exothermic conversion reaction of a synthesis gas (a mixture of carbon monoxide and hydrogen) to methane is carried out:

$$CO + 3H_2 \rightarrow CH_4 + H_2O + Q \qquad (1)$$

At lower temperatures, the opposite endothermic reaction for methane conversion occurs:

$$CH_4 + H_2O \rightarrow CO + 3H_2 - Q \qquad (2)$$

Reactions (1) and (2) proceeds simultaneously with the rapid water-shift reaction:

$$H_2 + CO_2 \leftrightarrow H_2O + CO \qquad (3)$$

Chemical equilibrium is shifted by changing of steam content in the reactor inputs. Reaction (1) proceeds in the methanator (device 1; Fig. 1) with a deficiency of steam and reaction (2) in the reformers (devices 2 and 4; Fig. 1) with a significant excess of steam.

2.2 Integrated system

A nuclear power plant with a chemical heat pump producing high-temperature heat is presented in Fig. 1 and its operation is explained here.

Water, after compression in a pump (device 10) to supercritical pressure of 25 MPa, is heated inside a reactor from 350°C to 625°C and directed to a supercritical pressure turbine connected through a shaft with an electrical generator for the electricity production. Part of supercritical water or superheated steam with temperature of 625°C or even higher is directed into a boiler (device 11) and a superheater (device 12). The heat required is delivered with the supercritical water/steam[1] from the first cycle in the SCW-CANDU nuclear reactor. Then, the superheated steam enters a high-pressure turbine (device 13) where it generates mechanical work as its pressure and temperature decrease. After reheating the steam in device 14, it is mixed with the methane-containing reaction mixture. The resulting gaseous flow enters two autothermal (adiabatic) methane reformers (devices 2 and 4) and two intermediate reheaters (devices 3 and 5). In the methane reformers the endothermic methane-conversion reaction of the mixture of hydrogen and carbon monoxide (Equation 2) occurs. Due to the endothermic nature of this reaction, the temperature of the gaseous flow decreases and, in order to increase the mechanical work from the low-pressure turbine (device 6), it is heated in devices 3 and 5. Downstream of the low-pressure turbine (device 6), the gaseous flow is cooled in a condenser (device 7) where the steam is separated into water and a reaction mixture as it condenses. The gaseous reaction mixture enters a compressor (device 8), is heated in a reheater (device 9) and is directed into the methanator (device 1). Reaction (1) is carried out in device 1 with a steam deficiency. A quantity

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[1] Steam superheated in peripheral fuel channels of the reactor may be supplied at subcritical pressures (so-called "superheated steam SCW CANDU reactor concept").

of heat Q_1 at temperature $T_1 \geq 600^{o}C$ is produced with the objective of utilizing it in a combined chemical water-splitting cycle to produce hydrogen. In such cycles, high-temperature heat is employed to drive some endothermic conversions in order to avoid or reduce the electricity consumption during the stage of electrolysis. Theoretically, the electricity consumption for electrolysis can be reduced by the value of the high temperature heat employed (Equation (6)).

The minimum pressure P_{min} in the power generation cycle should be increased because of the presence of uncondensed gases in the gaseous flow which enters the condenser (device 6); here, this pressure is chosen to be 1 atm (0.1013 MPa). In typical steam-water power generation cycles, the minimum pressure is about 0.003-0.005 MPa [10]. At these low pressures, uncondensed gases occupy a great volume, leading to a significant increase in the size of the condenser and pipes. At P_{min} = 1 atm steam condensation starts at a temperature of around $100^{o}C$ and some of the released heat Q_{rec} is used for preliminary water heating in the boiler (device 11). The excess released heat (Q_7 - Q_{rec}) in the condenser of the power generation cycle with a heat pump (Fig. 1) is transmitted to a standard power generation cycle with a minimum pressure P_{min} = 0.0314 atm (≈ 0.0032 MPa) (Fig. 2). There, it is used for preliminary water heating in the boiler.

3. Thermodynamic analysis

The thermodynamic analysis in this section assesses the effect of introducing the proposed heat pump on the thermal efficiency of the SCW-CANDU power generation plant.

3.1 Assumptions and data

The general assumptions applied in the analysis follow: (i) energy losses due to mechanical friction are negligible, (ii) thermodynamic and chemical equilibria are achieved at the outlet of the methanator (device 1) and methane reformers (devices 2 and 4), and (iii) the performance of the turbines and compressors is considered ideal.

Property data are evaluated using the following simplifications: (i) all gases except steam are modeled as ideal, (ii) thermodynamic data for liquid water and steam are taken from the NIST standard reference database (version 7.0), (iii) thermodynamic properties of others gases are taken from [11], and (iv) thermodynamic properties of gaseous mixtures are calculated assuming an additive input of the components.

3.2 Analysis

The general parameters used in the analysis of nuclear power generation cycles with a heat pump (Fig. 1) and without it (Fig. 2) are listed in Table 1. The temperatures of gaseous mixtures and steam at the output of the reheaters (devices 3,5,9,12 and 14 in Fig. 1; device 1 in Fig. 2) and superheaters (device 12 in Fig. 1 and device 6 in Fig. 2), where heat transfer with a nuclear reactor carrier occurs, are taken equal to T_{max} = 873 K. The high-potential heat is generated in the methanator (device 1, Fig. 1). Assuming that the inlet and outlet temperatures are even, i.e., $T_1^{out} = T_1^{in}$ = T_{max} = 873 K, the heat can be supplied at a temperature not lower than 873 K.

An absence of inert gases in the mixture with steam in the standard cycle (Fig. 2) permits lowering the minimum pressure P_{min} and condensation in device 3 at a constant and minimum temperature T_{min}. In the case where a heat pump is introduced (Fig. 1) this condensation (device 7) starts at a temperature of about 373 K and finishes at T_{min} = 298 K. The released heat is used to heat water downstream of the pump (device 10) and can be used to heat water in a standard nuclear power generation cycle (Fig. 2) if the two technologies are combined. Clearly, an increase in P_{min} for the scheme with a heat pump leads to a reduction in the power generated. Further details are presented in the next section with some results and their discussion.

4. Results and discussion

The results of the thermodynamic analysis are listed in Tables 2-6.

4.1 Energy balances

Tables 2 and 3 present energy balances. Data are given per 20 moles of steam circulated in the considered schemes (Figs. 1 and 2). The work obtained in the cycle must be equal to the difference between the consumed and released heat. As seen in these tables, the mechanical work (power) generated in the standard cycle (Fig. 2) is higher than that generated in the scheme with a heat pump (Fig. 1). The high-potential heat with a temperature equal to or higher than 873 K has a magnitude of Q_1 = 94.2 kJ. The composition of the gaseous flow in the heat pump cycle is presented in Table 4. In the methanator (device 1), H_2, CO and CO_2 are converted to CH_4, increasing its quantity from 0.39 to 0.89 moles, and heat is released. In the methane converters (devices 2 and 4), the opposite process occurs: in an excess of steam, methane is converted to hydrogen, carbon monoxide and carbon dioxide. The heat content and temperature of the gaseous flow in the reactors decreases (see Table 5) but this reduction is compensated for in the reheaters (devices 3 and 5). As seen in Table 5, water condenses out of the mixture of gases in the condenser (device 7, Fig. 1) at a variable temperature, i.e., T_7^{in} = 368 K to T_7^{out} = 298 K. Some of the heat Q_{rec} released in the condenser can be recovered for preliminary water heating in the boiler (device 11) from 298 to 368 K.

4.2 Efficiencies

Table 6 lists efficiency indicators for the compared schemes. The energy (or thermal) efficiency of the schemes are evaluated as

$$\eta_T^{(i)} = \frac{W_i}{Q_{nuc}^{(i)}} \tag{4}$$

where index *i* takes on a value of 1 or 2 for the schemes in Figs. 1 and 2, respectively, W_i is the work produced, and $Q_{nuc}^{(i)}$ is the heat released by the SCW-CANDU nuclear reactor and consumed by the second cycle of the overall power generation plant. Values for *W* and Q_{nuc} are given in Tables 2 and 3. Here, Q_{nuc} is equal to the sum of the consumed heats (taken with opposite signs) in the schemes. Taking into account that nuclear heat consumption Q_{nuc} in the scheme with a heat pump can be reduced by Q_{rec} (Table 6, column 3), its thermal efficiency can be written as follows:

$$\eta_T^{(1)} = \frac{W_1}{Q_{nuc}^{(1)} - Q_{rec}} \tag{5}$$

where the indexes refer to scheme 1. The thermal efficiencies for schemes 1 and 2 are found to be 0.48 and 0.37, respectively. These data favor the standard scheme (scheme 2).

We now assume that electricity is employed in the system where low-temperature electrolysis and chemical decomposition of water are applied simultaneously, like in Cu-Cl and UT-3 processes. Applying a general approach to determine the efficiency of chemical water decomposition, the following expression for hydrogen production can be inferred:

$$Ex_{H_2} = \eta_e W + Q_1 (T \geq 873K) \tag{6}$$

where Ex_{H_2} is the exergy of hydrogen; η_e is the low-temperature electrolysis efficiency; *W* is electrical work, and Q_1 is an external heat supply at a temperature higher than or equal to 600°C. Then the efficiency for nuclear heat utilization for hydrogen production is expressible as follows:

$$\frac{Ex_{H_2}}{Q_{nuc}} = \eta_e \left(\frac{W + Q_1/\eta_e}{Q_{nuc}} \right) = \eta_e \eta_T^{H_2} \tag{7}$$

$$\eta_T^{H_2} = \frac{W + Q_1/\eta_e}{Q_{nuc}} \tag{8}$$

where $\eta_T^{H_2}$ is thermal efficiency of nuclear energy use, calculated assuming high-temperature heat generated in the heat pump is employed for hydrogen production in low-temperature water decomposition processes. The efficiency $\eta_T^{H_2}$ for the nuclear power generation cycle with a heat pump is calculated for a typical electrolysis efficiency $\eta_e = 0.72$ [4] and listed in Table 6, column 6. Since the values of *LHV* and exergy Ex_{H_2} for hydrogen are almost equal we apply the same value of electrolysis efficiency (on the basis of hydrogen *LHV*) in the present analysis. In line with Equation (8) for the standard nuclear power generation cycle (Fig. 2), $\eta_T^{H_2} = \eta_T$. It is seen in this table that $\eta_T^{H_2}$ for the cycle with a heat pump is lower than that for standard one. The equilibrium composition in the catalytic reactors corresponds to the conversion of one mole methane with steam and, therefore, depends on the steam/methane ratio ($\upsilon_{H_2O}/\upsilon_{CH_4}$) in the chemical heat pump. As shown in Fig. 3, decreasing the steam/methane ratio leads to increasing values of Q_1 (calculated per mole of steam) and $\eta_T^{H_2}$. Nonetheless, it should be noted that augmenting the methane content, and its derivatives carbon monoxide and hydrogen, in the heat pump working medium results in an increased pump scale.

4.3 Further discussion

Analyzing values for the recovered heat Q_{rec} = 105.1 kJ (Table 6) and the low-temperature heat released in the condenser (device 7, Table 2) Q_7 = 918.2 kJ, it is seen that only a small part of this heat is utilized. Most of the low-potential heat can be employed for preliminary water heating in the boiler of the standard nuclear power generation scheme (Fig. 2). This observation means that cogeneration is possible from the standard nuclear power generation cycle and a heat pump. The maximum degree of such cogeneration *N* is estimated as follows:

$$n \leq N = \frac{Q_7 - Q_{rec}}{Q_{rec}} \tag{9}$$

where Q_7 is the heat released in the condenser of the scheme with a heat pump and Q_{rec} is the heat which could be utilized for heating a certain amount of water (20 mol in our case) in a boiler. The value *n* = 0 means no cogeneration occurs, *n* = 1 means that 20 mol of water in the standard nuclear power generation cycle are heated by the heat from the condenser of the cycle with a heat pump, and *n* = *N* means that *N**20 moles of water are heated in this way. Increasing values of *n* increases the relationship between the power capacities of the two schemes. The formulas for η_T and $\eta_T^{H_2}$ for a combined system reflect this dependence as follows:

$$\eta_T = \frac{nW_2 + W_1}{n(Q_{nuc}^{(2)} - Q_{rec}) + (Q_{nuc}^{(1)} - Q_{rec})} \tag{10}$$

$$\eta_T^{H_2} = \frac{nW_2 + W_1 + {}^{Q_1}\!/_{\eta_e}}{n(Q_{nuc}^{(2)} - Q_{rec}) + (Q_{nuc}^{(1)} - Q_{rec})} \tag{11}$$

where the indexes refer to scheme 1 or 2.

The efficiencies η_T and $\eta_T^{H_2}$ as a function of a cogeneration degree n for the cases $\upsilon_{H_2O}/\upsilon_{CH_4}$ = 10 and 20 are presented in Fig. 4. The values of thermal efficiencies η_T coincide for both cases and $\eta_T^{H_2}$ is slightly greater for the case $\upsilon_{H_2O}/\upsilon_{CH_4}$ = 10. It follows from this graph for n of about 3 the thermal efficiency η_T of a combined system is equal and $\eta_T^{H_2}$ is greater than the standard one. This is achieved as a result of reducing the power generation capacity of the scheme with a heat pump (this reduction is proportional to *n*) in respect to the standard one. Fig. 5 represents another principle regarding the utilization of released heat which avoids compromising the power generation capacity when a chemical heat pump is applied.

5. Conclusions

A heat pump that permits an increase in the temperature of the heat transferred from the first cycle in a SCW-CANDU nuclear reactor is proposed. This heat pump employs a catalytic methane conversion reaction where the reaction mixture of methane, steam, hydrogen, carbon monoxide and carbon dioxide is the working medium. Heat transfer to an external consumer occurs during methane synthesis and its absorption during the adiabatic (autothermal) methane conversion to hydrogen and carbon monoxide. The reaction shift from exothermic to endothermic and back is achieved by changing the steam concentration in the reaction mixture. This heat pump is implemented in the second power generation cycle of a SCW-CANDU nuclear plant.

A preliminary comparative thermodynamic analysis is conducted of the combined system comprising a SCW nuclear power generation plant and a chemical heat pump, which provides high-temperature heat to a thermochemical water decomposition cycle for hydrogen production.

Applying the proposed chemical heat pump improves utilization of nuclear energy at least by 2% without jeopardizing nuclear reactor safety. Based on the analysis an advanced design of a combined nuclear power generation plant with a chemical heat pump is proposed. Further use of exergy analysis to this scheme is the subject of ongoing research by the authors.

Acknowledgement

The financial support of an Ontario Premier's Research Excellence Award, the AUTO 21 Network of Centres of Excellence (NCE) and the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged.

Nomenclature

Ex	exergy, kJ
LHV	lower heating value, kJ
N	maximum value of cogeneration factor
n	cogeneration factor
P	pressure, atm
Q	heat, kJ
SCW	supercritical water
T	temperature, K
W	work, kJ

Greek Letters

η_e	low-temperature electrolysis efficiency
η_T	thermal efficiency
$\eta_T^{H_2}$	thermal efficiency of hydrogen production
υ	mole

Subscripts

max	maximum
med	medium
min	minimum
nuc	nuclear
rec	recovered

Superscripts

in	input
out	output

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Table 1. Parameters for the two nuclear power plant cycles.

Power generation cycle	P_{max} **atm**	T_{max} **K**	T_1^{out} **K**	P_{med} **atm**	P_{min} **atm**	T_{min} **K**
Nuclear power generation cycle with a heat pump (Fig. 1)	200	873	873	50	1	298
Standard nuclear power generation scheme (Fig. 2)	200	873	n/a	50	0.03	298

Table 2. Work and heat flows and energy balance for the nuclear power generation cycle with a high-temperature heat pump (Fig. 1).*

<table>
<tr><td></td><td colspan="5">Device</td></tr>
<tr><td>Energy</td><td>6</td><td>8</td><td>10</td><td>13</td><td>Total</td></tr>
<tr><td>Mechanical work, kJ (generated (+), consumed (-))</td><td>437.5</td><td>-58.6</td><td>-7.1</td><td>156.2</td><td>528.0</td></tr>
</table>

<table>
<tr><td></td><td colspan="9">Device</td></tr>
<tr><td></td><td>1</td><td>3</td><td>5</td><td>7</td><td>9</td><td>11,12</td><td>14</td><td>Mix[**]</td><td>Total</td></tr>
<tr><td>Heat, kJ (released (+), consumed (-))</td><td>94.2</td><td>-69.5</td><td>-26.0</td><td>918.2</td><td>-12.6</td><td>-1228.9</td><td>-203.07</td><td>-0.4</td><td>-528.0</td></tr>
</table>

* Data are given per 20 moles of water circulated in the system.

** Due to a steam enthalpy drop when decreasing its partial pressure as it is mixed with the reaction mixture, a negligible amount of heat is required to maintain a constant temperature at the inlet of methane converter 2.

Table 3. Energy balance of the standard nuclear power generation cycle (Fig. 2).*

<table>
<tr><td></td><td colspan="4">Device</td></tr>
<tr><td>Energy</td><td>2</td><td>4</td><td>7</td><td>Total</td></tr>
<tr><td>Mechanical work, kJ (generated (+), consumed (-))</td><td>543.7</td><td>-7.3</td><td>156.3</td><td>692.6</td></tr>
<tr><td></td><td colspan="4">Device</td></tr>
<tr><td></td><td>1</td><td>3</td><td>5,6</td><td>Total</td></tr>
<tr><td>Heat, kJ (released (+), consumed (-))</td><td>-203</td><td>739.6</td><td>-1229.2</td><td>-692.6</td></tr>
</table>

* Data are given per 20 moles of water circulated in the system.

Table 4. Composition of the gaseous flows circulated in the high-temperature heat pump.

Devices	**Flow**	**Composition**				
		CH_4	**H_2O**	**H_2**	**CO**	**CO_2**
1	Input	0.39	0.11	2.43	0.02	0.59
	Output	0.89	1.10	0.44	0.01	0.10
2	Input	0.89	21.10	0.44	0.01	0.10
	Output	0.52	20.36	1.91	0.01	0.47
4	Input	0.52	20.36	1.91	0.01	0.47
	Output	0.39	20.10	2.43	0.02	0.59
7	Input	0.39	20.10	2.43	0.02	0.59
	Output	0.39	0.11	2.43	0.02	0.59

Table 5. Input and output working-fluid temperatures and pressures for devices in the nuclear power generation cycle with a high-temperature heat pump (Fig. 1).

Devices	**T_{in}, K**	**T_{out}, K**	**P_{in}, atm**	**P_{out}, atm**
1	873	873	50	50
2	873	800	50	50
3	800	873	50	50
4	873	845	50	50
5	845	873	50	50
6	873	368	50	1
7	368	298	1	1
8	298	779	1	50
9	779	873	50	50
10	298	298	50	200
11,12	298	873	200	200
13	873	636	200	50
14	636	873	50	50

Table 6. Efficiency indicators for the cycles considered*.

Scheme	**W, kJ**	**Q_{rec}, kJ**	**η_T**	**$Q_1(T \geq 873$ K), kJ**	**$\eta_T^{H_2}$**
Nuclear power generation cycle with a high-temperature heat pump (Fig. 1)	528.0	105.1	0.37	94.2	0.46
Standard nuclear power generation cycle (Fig. 2)	692.6	n/a	0.48	n/a	0.48

* Data are given per 20 moles of water circulated in the system.

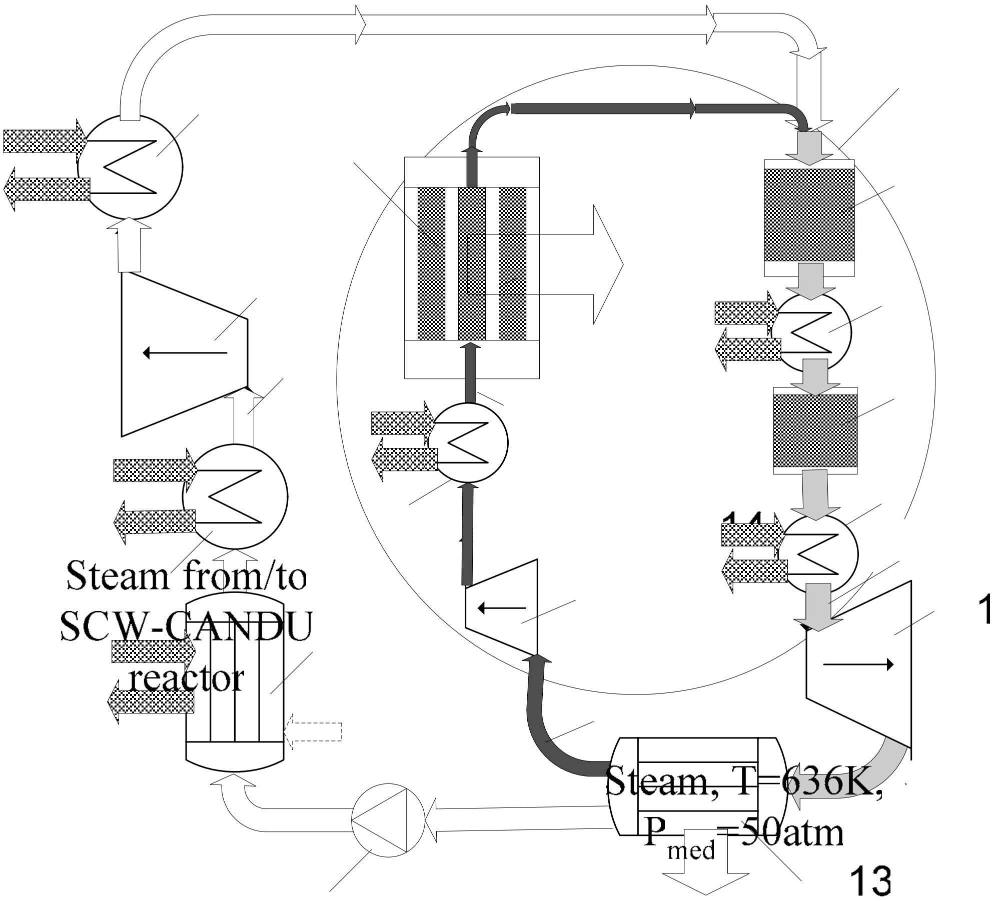

Figure 1. Implementation of a high-temperature heat pump into the second power generation cycle of a SCW-CANDU nuclear plant. Numbers indicate devices according to the following legend: 1: methanator; 2,4: autothermal methane converters; 3,5,9,14: reheaters; 6: low-pressure steam turbine; 7: condenser; 8: compressor; 10: pump; 11: boiler; 12: superheater; 13: high-pressure steam turbine.

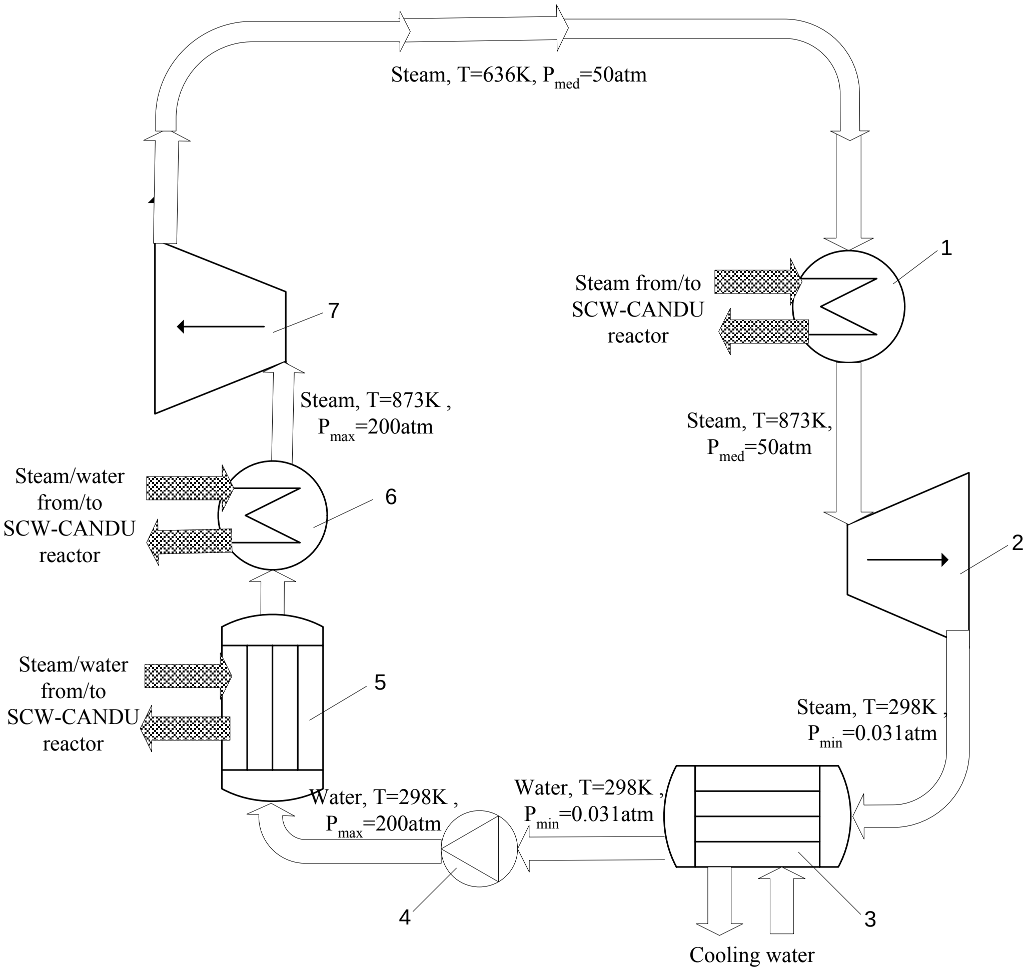

Figure 2 Simplified schematic of the standard second power generation cycle in a SCW-CANDU nuclear plant. Numbers indicate devices according to the following legend: 1: reheater; 2: low-pressure steam turbine; 3: condenser; 4: pump; 5: boiler; 6: superheater; 7: high-pressure steam turbine.

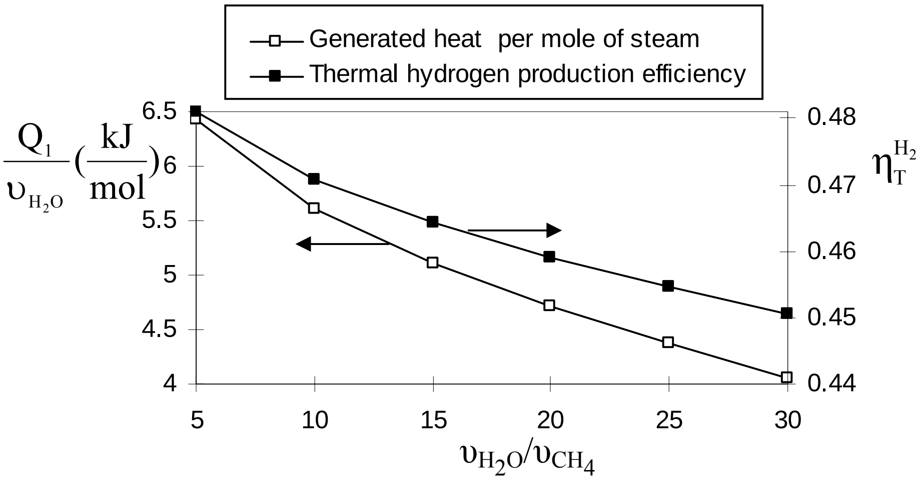

Figure 3. Variation of the specific heat (per mol of steam) generated in the heat pump $\frac{Q_1}{\upsilon_{H_2O}}$ and hydrogen production efficiency $\eta_T^{H_2}$ with the steam-methane ratio $\upsilon_{H2O}/\upsilon_{CH4}$ in the chemical heat pump working medium.

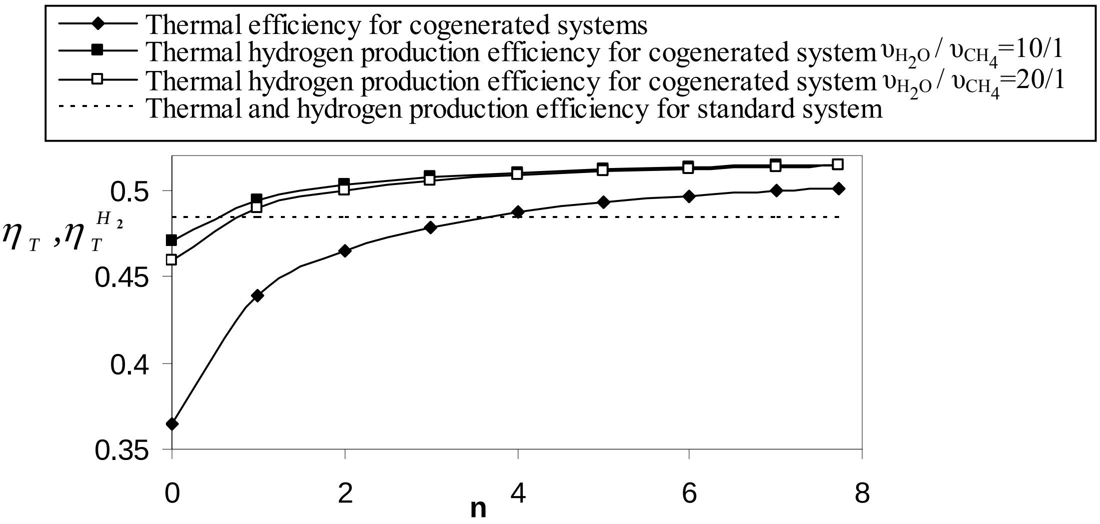

Figure 4. Variation of thermal and hydrogen production efficiencies η_T and $\eta_T^{H_2}$ with cogeneration degree *n*.

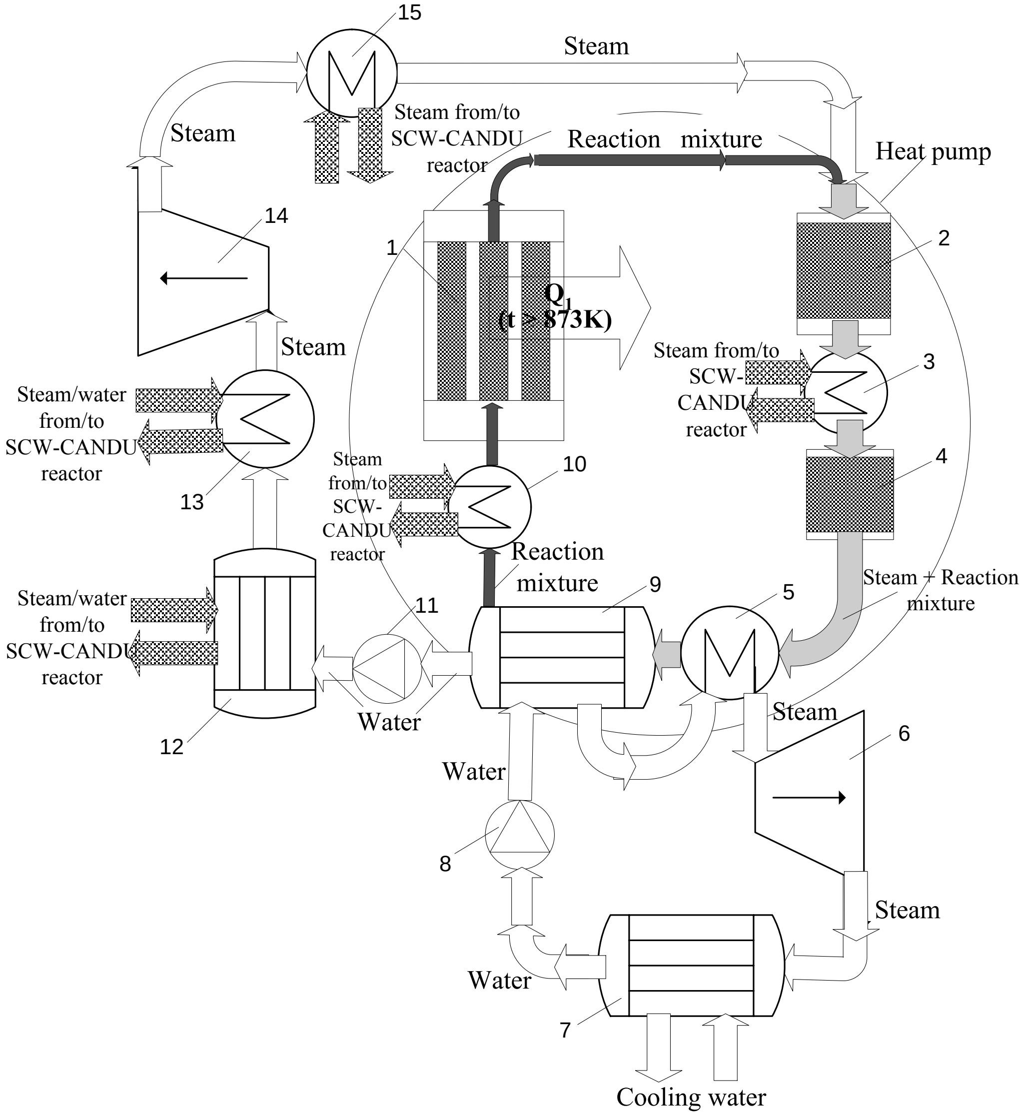

Figure 5. Implementation of an advanced scheme involving a heat pump into the second power generation cycle of a SCW-CANDU nuclear plant. Numbers indicate devices according to the following legend: 1: methanator; 2,4: autothermal methane converters; 3,5,10,15: reheaters; 6: low-pressure steam turbine; 7: low-pressure condenser; 8,11: pumps; 9: high-pressure condenser; 12: boiler; 13: superheater; 14: high-pressure steam turbine.