CLEAN ENERGY AND HYDROGEN FOR OIL SANDS DEVELOPMENT WITH CANDU SCWR NUCLEAR REACTORS AND CU-CL CYCLES

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Abstract

In this paper, the unique capabilities and advantages of SCWR technology for cleaner oil sands development are discussed from two perspectives: lower temperature steam generation by supercritical water for steam assisted gravity drainage (SAGD), and hydrogen production for oil sands upgrading by coupling SCWR with the thermochemical copper-chlorine (Cu-Cl) cycle. The heat requirements for bitumen extraction from the oil sands and the hydrogen requirements for bitumen upgrading are evaluated. A conceptual layout of SCWR coupled with oil sands development is presented. The reduction of CO_2 emissions due to the use of SCWR and thermo chemical hydrogen production cycle is also analyzed.

Keywords: oil sands, SAGD, nuclear power, thermochemical hydrogen production

1. Introduction

With the world population aiming at improving its living standards, the demand on oil supplies is increasing to meet these aspirations. According to past studies [1-4], oil today accounts for 35% percent of global energy supply, which is the largest share of any form of energy. The world demand for oil has multiplied from 11 million barrels per day (mbd) in 1950, to 57 mbd in 1970, to around 85 mbd today. According to the report of CERA in 2009 [2], oil will still have a central role in the world energy supply in 2035 and Alberta's oil sands will likely move from the fringe to the center. The oil sands have become one of the most important sources of oil supply growth in the past decade, as production has more than doubled from 0.6 mbd in 2000 to 1.3 mbd by 2009. By 2035, oil sands production is projected to range from 2.3 mbd to 6.3 mbd [2].

However, reducing the negative impacts of oil sands development on the environment is a major responsibility, particularly with the concerns about climate change. A balance between the will of improving our living standards, and worsening our environment, is needed. The oil sands, as a source of petroleum, encapsulate the challenges of approaching the balance [5]. The environmental and efficiency challenges for Alberta's oil sands are compelling cases for research and development into cleaner extraction and upgrading technologies.

There are various techniques and technologies for oil extraction. In addition to surface mining, steam assisted gravity drainage (SAGD, [9, 10, 16]) was developed in the 1980s as an *in situ* technology and was adopted quickly since the mid 1990s. In SAGD, a pair of horizontal wells is drilled in the oil sands and steam is injected into the upper well (injection well). After the oil sands region is soaked and softened, bitumen flows to the lower well (production well) and it is then pumped to the surface for further processing. Cyclic Steam Stimulation (CSS, [8]) is another method using steam, but with only one well. The steam is injected to the well for a certain amount of time to heat the oil in the surrounding reservoir, and then oil is produced out of the same well after soaking and softening of the oil sands.

Like CSS and SAGD, in the technology of toe to heel air injection (THAI, [12]), THAI technology also uses heat to soften the bitumen. But heat is generated underground by the combustion of a small portion of the bitumen in the ore body. Air is injected into an injection well to provide oxygen for the combustion. The THAI technology is expected to produce fewer GHGs and lower water use. Another technology is vapor extraction (VAPEX, [11]). The principle is similar to SAGD but instead of steam, hydrocarbon solvents are injected into the upper well to dilute and slightly upgrade the bitumen.

Cold heavy oil production with sand (CHOPS) is used as an important production approach in unconsolidated sandstones. Thousands of wells in Canada are now stably producing oil through CHOPS [6, 7].

Regardless of the differences of the above methods, immense heat or steam is required to soak, soften and upgrade the oil sands by most of the methods. After the extraction of bitumen from underground, further upgrading is required to convert bitumen to conveyable and usable synthetic crude oil. This upgrading not only needs much heat, but also needs large amounts of hydrogen for hydrotreating [13].

To provide the thermal energy, steam and hydrogen for oil sands development, a nuclear power plant that links to thermochemical hydrogen production can be used [18]. The focus of this paper will examine the energy and hydrogen requirements of the oil sands development. Then, according to the estimates, the role and arrangement of SCWR for the oil sands development will be discussed.

2. Steam temperature in SAGD and bitumen upgrading

In the technology of SAGD, the temperature of steam injected into the well is influenced by various factors such as the bitumen composition, bitumen properties, sand type, the composition and the oil well pressure. The maximum temperature is limited by its pressure, which should be below the fracture pressure of the rock mass [16]. In the production well, the steam is controlled just below saturated conditions to prevent steam vapor from entering the well bore and diluting oil production.

The bitumen is upgraded after it is extracted from the oil sand wells. The temperature required by the upgrading depends strongly on the bitumen properties, cracker types, processing methods and upgrading degree [18, 39, 46]. For example, the bitumen can be either upgraded into synthetic crude oil, or into more transportable and lighter oils after cracking and addition of hydrogen.

Table 1 lists various temperatures under different conditions for bitumen extraction and upgrading, including lab, oil field and refinery data. Since the steam for bitumen extraction and the heat for upgrading may be directly transferred from a nuclear power station, it is important to know the temperature level of the power plant. Table 2 gives the temperature of current CANDU reactors of Canada, and future supercritical water-cooled reactors (SCWRs) that are being investigated by various countries.

The practical operating temperature in the oil fields for bitumen extraction is in the range of 200-300°C, which is equivalent to the outlet temperature of current Canada's CANDU reactors. If the steam for bitumen extraction in SAGD is directly generated from the outlet stream of nuclear reactors, the current CANDU temperature may not be high enough to supply the steam for the bitumen extraction. That explains some investigators are searching for lower temperatures for SAGD as shown in the lab experiments of Table 1.

If the steam for bitumen extraction from oil wells is generated from electrical power, the required temperature can be achieved. However, the maximum overall thermal efficiency to generate steam is unlikely to exceed 30-35% because this range is also the conversion efficiency from nuclear heat to electrical power [29-32].

By comparison, the temperature range of SCWRs is 467-650°C, which is at least 150°C higher than the temperature level of SAGD, indicating that the steam for bitumen extraction in SAGD can be directly generated from the heat of the supercritical water of SCWRs. The SCWR maximum temperature of 620-650 °C can provide a 300°C temperature difference with the temperature of SAGD.

The overall thermal efficiency of using supercritical water to generate steam also depends on the conveying distance of the supercritical water. Figure 1 shows the conceptual layout of the integration of SCWR and oil extraction. A bypass line is opened at the outlet of the SCWR core (point A) to convey the supercritical water to generate steam for SAGD. The conveying distance of lines L_{BC} and L_{DE} may have a significant influence on the heat loss. Since the CANDU SCWR has the maximum temperature of all SCWRs, it is anticipated that the heat can be transferred over a longer distance than other SCWRs.

From the aspect of reducing heat losses, it is advantageous that the SCWR is constructed close to oil fields if the steam for SAGD is directly generated from supercritical water. The dependence of the heat loss on the conveying length in under investigation at the University of Ontario Institute of Technology (UOIT).

As to the upgrading of bitumen, similar conclusions can be obtained. The required temperature lies in the range of 350-550°C, which can only be satisfied by CANDU SCWR if the heat for upgrading is directly supplied by the nuclear reactor coolant.

Table 1 Temperature of bitumen extraction and upgrading

Bitumen extraction temperature in steam assisted gravity drainage (SAGD)				
T, °C (Steam used in SAGD)	**Type of extracted bitumen**	**Sand type**	**Oil field / lab data**	**Reference**
240-300	N/A	N/A	oil field Alberta	[15]
270	N/A	N/A	oil field Alberta	[26]
> 200	Viscosity < 2000cps	N/A	oil field Alberta	[27, 28]
139 - 144	12.4 API	Limestone	Lab	[21]
106	0.12 Pas at 106°C	glass beads	Lab	[20]
115	N/A	Silica sand	Lab	[22-24]
132 - 147	12.8 API	limestone	Lab	[25]
Bitumen upgrading temperature				
T, °C (Upgrading /cracking)	**Type of upgraded oil**	**Processing / reactor type**	**Refinery plant/ lab data**	**Reference**
350 - 530	Athabasca bitumen	Thermal cracking, fluidized bed	Lab	[40]
380 - 460	Canada bitumen	hydrothermal visbreaking, in supercritical water	Lab	[41]
400	Fort McMurray (Alberta) oil sands	Natural zeolite cracking	Lab	[42]
450 - 550	Heavy oil	Treated zeolite catalytic cracking	Refinery plant	[43]
500	Alberta bitumen	Delayed coking	Refinery plant	[13]
300-400	Alberta bitumen	hydrotreating	Refinery plant	[13]
450	heavy oil	API 618 standards upgrading	Refinery plant	[44]
525	Alberta bitumen	hydrocracking	Refinery plant	[45]
300-400	Canada bitumen	Fixed bed, removal of S, N and O.	N/A	[18]
410-420	Canada bitumen	Single cracker, increase H/C ratio,	N/A	[18]
470-510	Canada bitumen	Fluid catalytic cracker	N/A	[18]
N/A: Not applicable because the information was not reported in the reference.				

Table 2 Temperature of current CANDU reactors of Canada and future SCWRs

Temperature of coolant(a), °C	310	324	330	620-650	565-600	467-565	500
Reactor type	CANDU-6 Heavy water cooled	CANDU ACR Heavy water cooled	CANDU-6 Heavy water cooled, with Calandria reduction	SCWR Light water cooled	SCWR Light water cooled	SCWR Light water cooled	SCWR Light water cooled
Time	Current	Current & future, Gen III+	Current & future	Future Gen IV	Future Gen IV	Future Gen IV	Future Gen IV
Fuel type	Natural fuel	Slightly enriched fuel	Natural fuel	Enriched fuel	Enriched fuel	Enriched fuel	Enriched fuel
Country	Canada	Canada	Canada	Canada	US	Japan	China
Reference	[29, 30]	[31]	[32]	[33, 34]	[35]	[36, 37]	[38]
(a): The temperature refers to the temperature of the coolant that exits the reactor core, as this temperature determines the maximum temperature that the turbine steam can achieve.							

By comparison, if using electrical power to generate the heat for upgrading, the temperature requirement by SAGD can be achieved. The integration layout of SCWR and upgrading is also shown in Figure 1. It can be found that the conveying distance of line L_{FGH} may also have a strong influence on the heat loss, and it is advantageous that the SCWR is constructed close to the refinery.

3. Reduction of CO_2 emissions with the SCWR and Cu-Cl cycle

3.1 Heat requirements for bitumen extraction

From operating data of bitumen production, it was reported that about 28 cubic meters (1,000 cubic feet) of natural gas was used to generate heat to produce one barrel of bitumen from *in situ* projects, and about 14 cubic metres (500 cubic feet) for integrated projects [47]. The use of natural gas for the heat source not only consumes a portion of bitumen, but it also produces a vast amount of CO_2 emissions. Table 3 estimates the heat requirements in bitumen extraction, based on the predicted future production scales [2, 47] and the combustion heat of natural gas [48-49]. The CO_2 emissions are approximated on the basis of one mole of CH_4 producing one mole of CO_2, since the major composition of natural gas is CH_4 [49].

The number of nuclear reactors in Table 3 is estimated based on the assumption that each SCWR unit is around 1,000 MWe and the overall power generation efficiency is 45% [33-35]. The efficiency of the Generation III CANDU reactors for the estimate is 30% [30, 33-35]. As an approximation, if the heat for bitumen production is directly obtained from the SCWR coolant, then it is assumed that the nuclear heat of SCWR is not used to generate electricity, and the thermal efficiency of heat extraction for bitumen production is 100%. Conversely, if the heat for bitumen production is generated from electricity of SCWR, then it is assumed that the thermal efficiency of using the electricity to generate heat is 100%. These are idealizations that will provide basic and conceptual understanding of the challenges of oil sands development.

Table 3 shows that large amount of heat required to extract bitumen from oil sands. If each SCWR unit can generate 1,000 MWe power and each nuclear power plant has 6 units and all heat carried by SCWR coolant is used to produce hydrogen, then the total heat required from year 2015 to 2030 is equivalent to 3-6 SCWR plants. In comparison, if the heat is generated from electricity of SCWR plants, then the number of SCWR plants is about 7-14. If using the electricity of Generation III CANDU nuclear plants, then the number of plants is about 10 to 20.

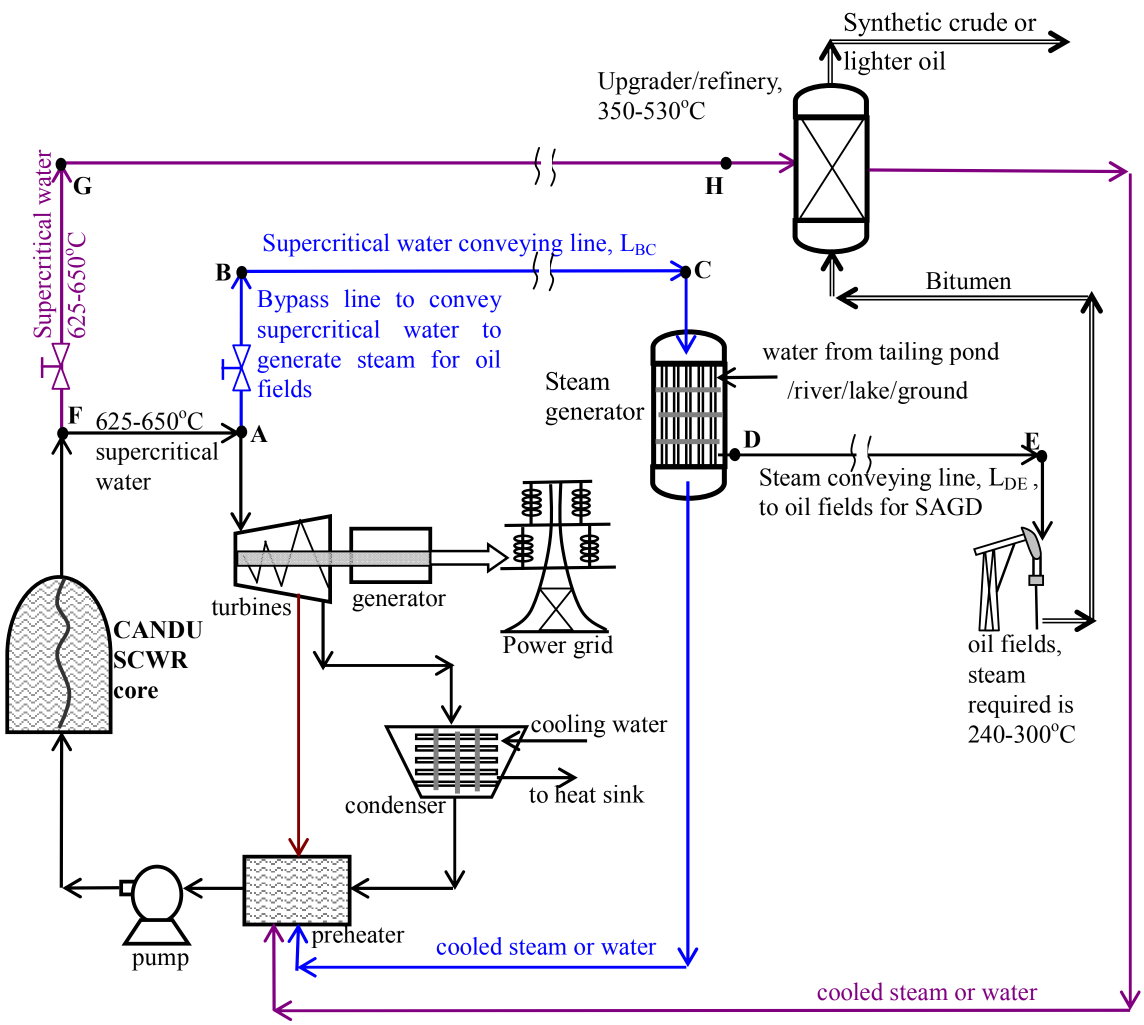

Figure 1 Conceptual layout of CANDU SCWR for bitumen extraction and upgrading
(Steam for SAGD is directly generated from supercritical water of SCWR)

Table 3 Reduction of CO_2 emissions due to the use of SCWR to supply heat for bitumen extraction from oil sands

Heat source for bitumen production	**Year**	**2015**	**2020**	**2025**	**2030**
	Bitumen production scale (10^6 barrels/day)	2.2	3.4	4.1	4.3
Natural gas	Natural gas volume for heating[(a)] (10^9 Ft^3/day)	3.3	5.1	6.2	6.5
Natural gas	Heat supplied by natural gas[(b)] (MWt)	40,233	62,178	74,979	78,636
Natural gas	CO_2 emissions resulting from its combustion for heat (10^6 tons/year)[(c)]	67.0	103.5	124.9	131.0
Natural gas	Compared with 2006 CO_2 emissions (% of 2006)[(d)]	12.3%	19.0%	22.9%	24.0%
If heat is directly extracted from SCWR coolant[(c)]	Number of SCWRs required (2,222 MWt/unit, equivalently 1,000 MW_e/unit)	18.1	28.0	33.7	35.4
If heat is directly extracted from SCWR coolant[(c)]	Number of SCWR plants required (6 SCWRs per plant)	3.0	4.7	5.6	5.9
From the electricity of SCWR	Number of SCWRs required (2,222 MWt/unit, equivalently 1,000 MWe/unit)	40.2	62.2	75.0	78.6
From the electricity of SCWR	Number of SCWR plants required (6 SCWRs per plant)	6.7	10.4	12.5	13.1
From the electricity of Gen-III Candu plants[(d)]	Number of Gen-III CANDU plants required (6 nuclear reactors per plant)	10.1	15.5	18.7	19.7

(a) To produce 1 barrel bitumen requires 1,500 ft^3 natural gas [43].
(b) The lower heating value of 1 standard ft^3 of natural gas is 252 kilocalories [48, 49].
(c) 1 mole CH_4 produces 1 mole CO_2.
(d) In 2006, the total CO_2 emissions of Canada were about 544.68 million tons [50].

It can be found from Table 3 that the CO_2 emissions from 2015 to 2030 are 12-24% of 2006 Canada's total CO_2 emissions, if natural gas is still used as the major heat source for bitumen extraction. To adopt SCWR to supply the heat for bitumen production can significantly reduce the CO_2 emissions.

3.2 Hydrogen requirements for bitumen upgrading

The hydrogen for bitumen upgrading can be supplied either from steam methane reforming, electrolysis, Cu-Cl thermochemical cycle or other methods. Operating data shows that upgrading a barrel of bitumen usually takes 2.4 – 4.3 kg of hydrogen [18, 51, 52]. For simplification purposes, in this paper, an average value of 3.3 kg H_2/barrel bitumen is adopted to calculate the hydrogen quantity for bitumen upgrading. Table 4 shows the reduction of CO_2 emissions due to the coupling of the Cu-Cl cycle with SCWR to supply hydrogen for bitumen upgrading.

Table 4 Reduction of CO_2 emissions due to the linkage of the Cu-Cl cycle with SCWR to supply hydrogen for bitumen upgrading

Hydrogen source	**Year**	**2015**	**2020**	**2025**	**2030**
	Bitumen upgrading scale (10^6 barrels/day)	2.2	3.4	4.1	4.3
Steam reforming of natural gas	Hydrogen required for upgrading[e] (tons/day)	7,480	11,560	13,940	14,620
Steam reforming of natural gas	CO_2 emissions from methane as reactant for SMR (10^6 tons/year)	30.0	46.4	56.0	58.7
	Compared with 2006 CO_2 emission (% of 2006)[f]	5.5%	8.5%	10.3%	10.8%
Cu-Cl cycle + SCWR	Heat supplied by SCWR to produce H_2, (MW_t) [g]	19,046	29,435	35,495	37,227
(Heat is directly extracted from SCWR coolant.)	Number of SCWR plants required to produce H_2 (1,000 MW_e/unit, 6 units/plant)	1.4	2.2	2.7	2.8

(e) Upgrading of a barrel of bitumen requires 2.4 – 4.3 kg hydrogen [18, 51, 52]. In this table, an average value 3.3 kg is adopted for approximations.
(f) In 2006, the total CO_2 emissions of Canada were 544.68 million tons [50].
(g) Using the Cu-Cl cycle, 220 MJ is required to produce 1 kg H_2 if assuming only 50% of the heat released by exothermic reactions of the Cu-Cl cycle is reused inside the cycle [53].

The heat required to supply the Cu-Cl cycle to produce hydrogen is calculated on the basis of process heat of each step of the Cu-Cl cycle. To produce 1 mole of hydrogen, the total required heat by all endothermic reactions is 555 kJ and the total released heat of all exothermic reactions is 232 kJ in the Cu-Cl cycle [53]. Therefore, assuming only 50% of the heat released by exothermic reactions of the Cu-Cl cycle is reused inside the cycle, to produce 1 kg of hydrogen in the Cu-Cl cycle, the net heat input to the cycle is:

$$(555 - 232*50\%)/2*1000 = 220 \text{ MJ/kgH}_2 \quad \text{(Cu-Cl cycle)} \qquad (1)$$

It can be found from Table 4 that the CO_2 emissions from year 2015 to 2030 are 5-11% of 2006 Canada total CO_2 emissions, if natural gas is still used as the major hydrogen source for bitumen upgrading. To couple the Cu-Cl cycle with SCWR to supply the hydrogen will signigicantly reduce the CO_2 emissions.

Table 5 gives the total reduction of CO_2 emissions if the use of natural gas is completely stopped. The reduction of CO_2 emissions from year 2015 to 2030 could be 18-35% of 2006 Canada's total CO_2 emissions.

Table 5 Emissions of CO_2 when using methane to supply heat for bitumen extraction and hydrogen for upgrading

Year	**2015**	**2020**	**2025**	**2030**
Bitumen production and upgrading scale (10^6 barrels/day)	2.2	3.4	4.1	4.3
CO_2 emissions from use of natural gas as the heat source of bitumen extraction and hydrogen source of upgrading, (10^6 tons/year)	97	150	180	190
Compared with the total CO_2 emissions of 2006 (% of 2006)(h)	18%	28%	33%	35%
(h) In 2006, the total CO_2 emissions of Canada were 544.68 million tons [50].				

4. Conclusions

The future SCWR of Canada can satisfy the temperature requirements of SAGD for bitumen extraction if the heat of SCWR coolant is directly used to generate steam for SAGD. The availability of the heat carried by SCWR is also influenced by the conveying distance of supercritical water and steam. In terms of thermal efficiency of heat transfer, it is advantageous that the SCWR is constructed relatively close to the oil fields.

This paper found that CO_2 emissions would increase by 18-35% from the year 2015 to 2030 if natural gas is still used as the major source of heat for bitumen extraction and hydrogen for bitumen upgrading. The application of SCWR to the oil sands industry can significantly reduce the CO_2 footprint of Canada, especially if it is coupled with the Cu-Cl hydrogen production cycle. The conceptual layout for the integration of CANDU SCWR and bitumen extraction and upgrading was also discussed in this paper.

5. Acknowledgements

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