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THERMODYNAMIC ANALYSIS OF A COMBINED VAPOR POWER CYCLE AND ABSORPTION REFRIGERATION SYSTEM

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ABSTRACT

In this study, a combined steam turbine (ST) based vapor power cycle (VPC) and vapor absorption refrigeration system (VARS) is analyzed. The power cycle is reheat regenerative type with one reheater and two feed water heaters. A low pressure open water heater (OWH) and a high pressure closed water heater (CWH) are used for preheating the boiler feed water in the power cycle. The cooling tower (CT) and two water circulating pumps near the CT basin are also taken into consideration in the configuration for analysis. The bottoming water−LiBr VARS consists of the generator, condenser, expansion valve, evaporator, absorber, solution pump, solution heat exchanger (SHE) and a throttle valve. The power cycle uses coal and municipality solid wastes (MSW) as boiler fuels for steam generation. The exhaust flue gas leaving the boiler at high temperature is the source of heat for the generator of the VARS. All the components of the power cycle and the bottoming VARS are thermodynamically modelled. Coal and MSW compositions are known and fuel lower heating value and its chemical exergy are determined from known chemical composition. With fuel mass flow rate, boiler pressure, ST inlet temperature and condenser pressure as model input parameters, the net power output, energy and exergy efficiency of the power cycle are calculated and analyzed. It is found that the power cycle operated with MSW produces less power compared to the coal; however CO_2 and SO_2 emissions from the MSW fired power plant are less. Further with variation in the cooling load (CL) it is seen that generator heat required for vapor generation in the VARS generator increases with increase in CL. This in turn demands more exhaust heat utilization from the boiler leaving flue gas. Amount of steam produced in the boiler increases with decrease in flue gas exhaust temperature. This also causes an increase in the net power output and efficiency of the power cycle. Net power and overall efficiency of the coal fired power plant are 172.324 MW and 34.732% respectively at an exhaust gas temperature 300°C at 500 Ton of refrigeration (TOR) which increases up to 183.714 MW and 37.028% at 150°C. This is mainly due to increase in steam generation rate in the boiler from 169.609 kg/s to 181.357 kg/s with decrease in exhaust temperature from 300°C to 150°C.

INTRODUCTION

Increased concern for global warming and environment has stimulated active research interest in the development of vapor absorption refrigeration systems (VARSs) as an alternative to the vapor compression refrigeration systems (VCRSs). Chlorofluorocarbons (CFCs) used in VCRSs have large degree of ozone depletion potential and also a major source of greenhouse gases. HCFC, HC and HFCs are possible substitutes for CFCs in VCRS and as such, VCRS has many preferred refrigeration and air-conditioning applications. The advantages with VARS are that it can be operated with waste heat stream, non-conventional energy sources such as solar or geothermal energy and most importantly the use of CFCs as working fluid can be avoided. VARS helps reducing the emissions of greenhouse gases such as CO_2 [1]. However its COP is low compared to VCRS. Trygg and Amiri [2] made a comparison between vapor compression and absorption chillers for energy utility in district cooling and Swedish municipality industries. Aqua ammonia (NH_3–H_2O) and water–lithium bromide (H_2O–LiBr) solutions are the most widely used working fluid pairs in VARS. Many other solution pairs have also been investigated as possible alternatives to NH_3–H_2O and H_2O–LiBr which include Acetone–zinc bromide [3], water–monomethylamine [4] etc. Thermodynamic analysis of VARS is available in literature in plenty. Karamangil et al. [1] examined the performance of a VARS using H_2O-LiBr, NH_3-H_2O, NH_3-$LiNO_3$ solution pairs separately. They investigated the effects of operating temperatures, the effectiveness of solution, refrigerant and solution–refrigerant heat exchangers (SHE, RHE, SRHE) on performance using a developed software package. Kaynakli and Kilic [5] made a thermodynamic analysis of the H_2O-LiBr absorption refrigeration cycle evaluating the influences of generator, evaporator, condenser and absorber temperatures and effectiveness of heat exchanger on the thermal loads of various components and coefficients of performance. Kaynakli and Kilic [6] analyzed the energetic and exergetic performance of a single-stage H_2O–LiBr VARS. In VARS generator heat is supplied externally. In the above studies analysis of VARS is done without considering the source of heat for the generator. This can possibly be done in a situation where the source of heat is assumed to be available for supply of heat to the generator and as such it has nothing to do with the performance of the system providing heat for the VARS. However, when a VARS is considered along with the heat providing system, the performance of the two systems become interdependent; the performance of one will affect the other. E.g. Havelsky [7] in his work have shown the use of exhaust heat of internal combustion engine (ICE) combustion products and engine cooling as driving heat source for the VARS. Khaliq [8] proposed a trigeneration system combining a conventional gas turbine cycle (topping cycle) with a heat recovery steam generator for process heat and vapor absorption refrigeration (bottoming cycle) for the cooling purpose. Manzela et al. [9] reported on feasibility of using the IC engine exhaust gas as a source of energy for VARS where they presented an experimental study of an NH_3-H_2O absorption refrigeration system while evaluating the impact of the absorption refrigeration system on engine performance, exhaust emissions, and power economy. Analysis of solar powered VARS is reported by Assilzadeh [10] (H_2O-LiBr syetem), Mittal et al. [11] (H_2O-LiBr syetem) and Abu-Ein et al. [12] (NH_3-H_2O system). In our previous works [13,14] we analyzed a combined vapour power cycle (VPC) and VARS where the steam extracted from the ST was the source of heat for the VARS generator. In the present work we have analyzed a combined vapour power cycle (VPC) and VARS where the exhaust gas from boiler (flue gas) is used as a source of heat for VARS generator. The fuels for the boiler of the power plant are coal or MSW. MSW if utilized properly in the incineration/thermal power plant could reduce the problem of waste management while also reducing the dependence on other conventional fuels. Murphy and McKeogh [15] investigated four technologies viz. incineration, gasification, generation of biogas and utilization in a combined heat and power (CHP) plant, generation of biogas and conversion to transport fuel with MSW. Qui and Hayden [16] explored an approach to extracting energy from MSW more efficiently – MSW/ natural gas hybrid combined GT−ST cycles, utilizing MSW fuel in bottoming ST cycle. Souza-Santos and Ceribeli [17] presented a technical feasibility study of using MSW in a bubbling fluidized bed boiler for steam generation at 10 MPa and running a ST. The flue gas resulting from MSW burning in the boiler was cleaned and further utilized for driving a GT.

NOMENCLATURE

$\dot{E}$	energy loss (kW)
CT	Cooling Tower
h	enthalpy (kJ kg^{-1})
MSW	Municipal Solid Waste
$\dot{m}$	Mass flow rate (kg s^{-1})
TOR	tones of refrigeration
VARS	Vapor Absorption Refrigeration System
VPC	Vapor Power Cycle
X	concentration(kg LiBr/kg solution)

SUBSCRIPTS

A	absorber
C	VARS condenser
E	Evaporator
G	Generator
sp	solution pump
ss	strong solution
H_2O	water
ws	weak solution

SYSTEM CONFIGURATION

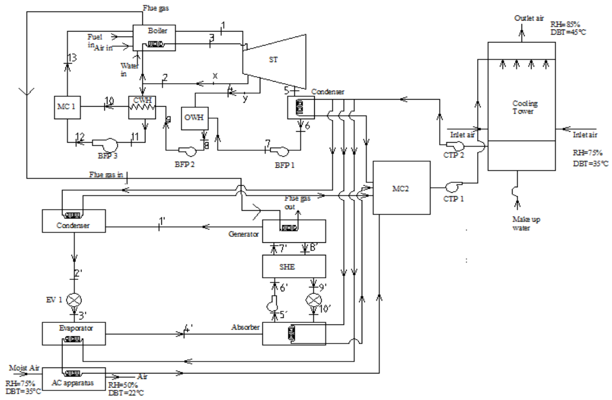

Fig.1 Schematic of the combined reheat regenerative vapor power cycle and water-LiBr VARS

The combined VPC and the VARS is shown in Fig.1. The steam power cycle employs one open feed water heater (OWH); one closed feed water heater (CWH) and a reheater. The bottoming cycle is a single effect H_2O-LiBr VARS consisting of the generator, condenser, expansion valve, evaporator, absorber, solution pump, SHE and a throttle valve. The steam cycle uses either coal or MSW fuels in the boiler furnace. The high pressure superheated steam (500°C) produced at 150 bar in the boiler enters the steam turbine (ST) and is first expanded to 30 bar. At this pressure, some steam is extracted for the CWH and remaining steam is reheated to the original superheated temperature. Remaining steam expands to the condenser pressure and is completely condensed in the condenser. The mixture is then pumped to the boiler pressure which again mixes with the high pressure condensed water from the CWH at the same boiler pressure. Cold water from the cooling tower (CT) basin is supplied to the condenser of the steam cycle and also to the condenser, absorber and evaporator of the VARS. The chilled water from the evaporator of the VARS passes through the air conditioning (A/C) apparatus before it mixes with return hot water streams from condenser of the steam cycle, condenser and absorber of the VARS in the mixing chamber 2. The mixed hot water stream is pumped to the wet CT for cooling of water by air. The cold water from the CT is then again routed through condenser of the steam cycle, condenser, absorber, evaporator and A/C apparatus of the VARS using another pump at the exit of the CT basin. The flue gas leaving the boiler is the source of heat for the VARS generator. Two flue gas temperatures at VARS generator inlet are considered viz. 150ºC and 300 ºC. The other input parameters are shown in Table 1. Chemical composition of coal is: carbon-60%, hydrogen-4%, oxygen-3%, sulphur-3%, nitrogen-2%, ash-24%, moisture-4%. MSW composition is: carbon-25%, hydrogen-3%, oxygen-20%, sulphur-0.3%, nitrogen-0.5%, ash-25%, moisture -25%.

Table 1: Assumed values of parameters

Parameter	Value
ST and pump isentropic efficiency	85%
Boiler pressure	150 bar
Reheat pressure	30 bar
Condenser pressure	0.1 bar
Terminal temperature difference in CWH	3°C
Cooling tower exit water temperature	25°C
VARS condenser exit water temperature	30°C
VARS absorber exit water temperature	30°C
VARS evaporator exit water temperature	10°C
Chilled water temperature at A/C apparatus inlet	10°C
Cooling tower inlet air temperature	25°C
Cooling tower inlet air relative humidity	40%
Cooling tower exit air temperature	35°C
Cooling tower exit air relative humidity	80%
Air mass flow rate though AC apparatus	4 kg/s
AC apparatus inlet air temperature	35°C
AC apparatus exit air temperature	25°C
AC apparatus inlet air relative humidity	75%
AC apparatus exit air relative humidity	50%
Refrigeration load	500-2500 TOR
VARS condenser temperature	35°C
VARS evaporator temperature	10°C
VARS absorber temperature	35°C
VARS generator temperature	80°C
Heat exchanger effectiveness	0.75

THERMODYNAMIC ANALYSIS

TOPPING VPC

The specific enthalpy and entropy at all the salient points of the VPC are calculated from International Associations for the properties of water and steam (IAPWS) formulation [18]. Steady flow energy equation (SFEE) is applied to the various system components for the purpose of finding work and heat transfer [13]. The CT is also analyzed and CT side pumping power is computed through calculation of pump total head details are given in [13]. Net power of the topping VPC is thus the ST power minus boiler feed pump (BFP) and CT side pumping power. Fuel mass flow rate is considered a model input parameter and its lower heating value (LHV) is calculated theoretically using equations of Ref.[19]. Complete combustion of fuel is considered with flue gas comprising of CO_2, SO_2 and water vapor and N_2. The energy lost with the flue gas is calculated using the procedure outlined in Ref. [13]. Fuel chemical exergy is also determined using correlation taken from Ref. [19]. The energy efficiency of the topping VPC is the ratio of net power to the fuel chemical energy while the exergy efficiency is the ratio of net power to the sum of fuel chemical exergy and thermo-mechanical exergy of air entering the boiler furnace.

BOTTOMING H_2O-LiBr VARS

Concentration of the strong and weak solution of the refrigerant as functions of operating temperatures is known [20].Thermodynamic properties such as specific enthalpy, entropy of the refrigerant (water) both in liquid and vapour state at various pressures and temperature are determined from International Associations for the properties of water and steam (IAPWS) formulation 1997 [18]. Similarly the thermodynamic properties of H_2O-LiBr solutions at various temperatures and concentration are calculated using the correlations proposed by Patek and Klomfar [21].

The CL in the evaporator (Q_E) is input to the thermodynamic model from which the mass low rate of refrigerant can be determined as given below.

$$\dot{m}_{H_2O} = \frac{Q_E}{h'_4 - h'_3} \quad (1)$$

The mass flow rate of strong and weak solution is calculated from equations [20].

$$\dot{m}_{ss} = \frac{\dot{m}_{H_2O} X_{ws}}{X_{ws} - X_{ss}} \quad (2)$$

$$\dot{m}_{ws} = \frac{\dot{m}_{H_2O} X_{ss}}{X_{ws} - X_{ss}} \quad (3)$$

$$COP = \frac{Q_E}{Q_G + W_{sp}} \quad (4)$$

The thermal load in the generator, absorber and condenser can be expressed as:

$$Q_G = \dot{m}_{H_2O} h'_1 + \dot{m}_{ws} h'_8 - \dot{m}_{ss} h'_7 \quad (5)$$

$$Q_A = \dot{m}_{H_2O} h'_4 + \dot{m}_{ws} h'_{10} - \dot{m}_{ss} h'_5 \quad (6)$$

$$Q_C = \dot{m}_{H_2O} \left(h'_1 - h'_2\right) \quad (7)$$

Q_E, Q_C and Q_A values give the mass flow rate of cooling water to be passed through these devices from heat balance.

RESULTS AND DISCUSSIONS

A computer program in C language was developed for simulating the combined power and cooling system. The CL is varied from 500 TOR (1750 kW) to 2500 TOR (8750kW). Table 2 shows the simulation results of the coal and MSW operated VPC corresponding to flue gas temperature of 300ºC at generator inlet.

Table 2. Performance variation of the coal and MSW operated topping VPC with evaporator CL (flue gas temperature 300ºC at generator inlet)

CL (TOR)		500	1000	1500	2000	2500
Net Power (MW)	Coal	172.324	171.915	171.469	170.980	170.446
	MSW	84.339	84.213	84.064	83.890	83.687
Steam generation rate (kg/s)	Coal	169.610	169.610	169.610	169.610	169.610
	MSW	81.698	81.698	81.698	81.698	81.698
Energy efficiency (%)	Coal	34.732	34.650	34.560	34.461	34.354
	MSW	35.551	35.498	35.435	35.362	35.277
Exergy efficiency (%)	Coal	32.772	32.694	32.609	32.516	32.415
	MSW	31.864	31.816	31.760	31.694	31.617

Net power and efficiencies (energy and exergy) decrease with CL in both the coal and MSW operated VPC. This is due to increase in pumping power requirement of the cooling tower side pumps at higher CL. Rate of steam generation in the boiler is not affected by CL variation. The lower heating value (LHV) of MSW (11861.60 kJ/kg) is significantly less compared to coal (24807.53 kJ/kg) due to its low carbon and high moisture content, therefore with same amount of fuel (20 kg/s), MSW fuel produces less amount of steam in the boiler and this reduces the net power output of the plant. Chemical exergy of MSW (13243.363 kJ/kg) is also less than that of coal (26315.804 kJ/kg). Since the net power produced by the VPC is less with MSW fuel, its LHV and chemical exergy are also less, therefore energy and exergy efficiencies do not change much due to fuel change in the boiler of the VPC.

COP of the bottoming VARS does not change with CL due to the fact that the generator heat load and solution pump work also increases proportionally. Heat load in the generator, absorber and condenser increases proportionately due to increase in mass flow rate of refrigerant, weak and strong solution at higher CL. These results corresponding to VARS performance at various CLs are shown in Table 3. The fuels (coal and MSW) have no effect on these results and hence these are same for both coal and MSW fuel. However, the CO_2 and SO_2 emissions in the flue gas product are significantly less in case of MSW fuel and the CL has no impact on these emissions. Rate of CO_2 emission for the coal operated VPC is 5.00 kmol/s and this is only 2.083 kmol/s in case of MSW. Similarly SO_2 emission rate which is 0.094 kmol/s in case of coal reduces to 0.009 kmol/s in case of MSW. This is due to low carbon and sulphur content in MSW composition.

Table 3. Variation of various parameters of the VARS cycle with variation of CL (flue gas temperature 300ºC at generator inlet)

CL (TOR)	500	1000	1500	2000	2500
COP	0.816	0.816	0.816	0.816	0.816
Q_G (kW)	2143.700	4287.401	6431.101	8574.801	10718.502
Q_A (kW)	2057.052	4114.105	6171.157	8228.209	10285.262
Q_C (kW)	1846.484	3692.968	5539.453	7385.937	9232.421
$\dot{m}_{ss}$ (kg/s)	5.239	10.477	15.716	20.954	26.193
$\dot{m}_{ws}$ (kg/s)	4.501	9.002	13.503	18.004	22.505
$\dot{m}_{H_2O}$ (kg/s)	0.738	1.475	2.213	2.950	3.688

The flue gas when supplied at 300ºC to the VARS generator, it leaves the generator at a temperature of 248.07 ºC in case of the coal operated VPC at 2500 TOR. This flue gas outlet temperature in case of MSW fuelled plant is however less (183.52 ºC). The generator outlet flue gas temperatures at other CLs are shown below in Table 4.

Table 4.Variation of flue gas temperature at outlet from VARS generator with variation in CL (flue gas temperature at generator inlet is 300ºC)

TOR		500	1000	1500	2000	2500
Flue gas temperature at Generator outlet (ºC)	Coal	289.67	279.32	268.93	258.52	248.07
	MSW	277.03	253.90	230.62	207.18	183.52

Cooling more than 2500 TOR is possible with flue gas entering the generator at 300ºC because minimum allowable temperature at which the flue gas is exhausted to the temperature is the range of 105−120ºC. However with 300ºC, the temperature difference between the flue gas and generator temperature (80ºC) will be very high, this will result in more irreversible losses in the generator. Therefore the system simulation was done also for a generator inlet flue gas temperature of 150 ºC. However with this inlet temperature, the maximum cooling that can achieved is 1300 TOR with the coal based flue gas (exit temperature 121.93ºC) and 600 TOR with MSW based flue gas(exit temperature 121.18ºC). At CL less than 1300 TOR and 600 TOR, the flue gas at generator outlet will anyhow be greater than 121.93ºC and 121.18ºC respectively for the two cases. Generator outlet flue gas temperature if falls below 120ºC then the sulphur present in the flue gas would form sulphuric acid (H_2SO_4) and this may corrode the pipelines and material of the generator.

When a generator inlet flue gas temperature is 150ºC, more steam is produced in the boiler of the topping VPC as more heat is utilized and accordingly the VPC will produce more power with higher efficiencies. The difference in performance of the coal fired topping VPC for these two cases of generator inlet flue gas temperature is shown in Table 5.

Table 5. Performance variation of the coal fired VPC with generator inlet flue gas temperature at 300 ºC and 150ºC

TOR		500	1000	1300
Net Power (MW)	300 ºC	172.324	171.915	171.652
	150 ºC	183.714	183.253	182.958
Steam generation rate (kg/s)	300 ºC	169.610	169.610	169.610
	150 ºC	181.357	181.357	181.357
Energy efficiency (%)	300 ºC	34.732	34.650	34.597
	150 ºC	37.028	36.935	36.876
Exergy efficiency (%)	300 ºC	32.772	32.694	32.644
	150 ºC	34.938	34.850	34.794

The performance of the bottoming VARS as it was independent of the boiler fuels; this variation of generator inlet flue gas temperature also has no impact on the VARS performance except the irreversible losses in the generator. The irreversibility in the generator will reduce due to decrease in temperature difference between the heat providing flue gas and the generator temperature (80ºC) which is fixed in the present study. E.g. the irreversibility in the VARS generator at CL of 1300 TOR with 300ºC inlet temperature of the coal based flue gas is 1854.269 kW and the flue gas leaves the generator at 273.09ºC. This generator irreversibility reduces to 760.438 kW when the coal based flue gas enters the generator at 150ºC. The detail calculation of irreversibility occurring in various system components is not shown in the present work. At CL of 1300 TOR, Q_G =5573.621 kW, Q_C =4800.859 kW, Q_A =5348.336 kW, $\dot{m}_{H_2O}$ =0.885 kg/s, $\dot{m}_{ws}$ =5.401 kg/s and $\dot{m}_{ss}$ =6.286 kg/s. For the MSW fired VPC, the difference in results of the MSW fired power plant for the two cases of generator inlet flue gas temperatures (300ºC and 150ºC) is shown in Table 6.

Table 6. Performance variation of the MSW fired VPC with generator inlet flue gas temperature at 300ºC and 150ºC

TOR		500	600
Net Power (MW)	300 ºC	84.339	84.316
	150 ºC	89.739	89.713
Steam generation rate (kg/s)	300 ºC	81.698	81.698
	150 ºC	86.985	86.985
Energy efficiency (%)	300 ºC	35.551	35.541
	150 ºC	37.827	37.816
Exergy efficiency (%)	300 ºC	31.864	31.855
	150 ºC	33.904	33.894

At CL, 600 TOR, Q_G =2572.440 kW, Q_C =2215.781kW, Q_A =2468.463kW, $\dot{m}_{H_2O}$ =1.918kg/s, $\dot{m}_{ws}$ =11.702 kg/s and $\dot{m}_{ss}$ =13.62 kg/s.

CO_2 and SO_2 emissions from the boiler of the topping VPC do not change with the generator flue gas inlet temperature. Their values are fixed and these only change with the change in fuel that is coal and MSW used in the boiler.

CONCLUSIONS

The following conclusions are drawn from the results discussed above.

1. LHV of MSW is significantly less compared to coal due to its low carbon and high moisture content. When MSW is used as fuel in boiler of the topping VPC, the amount of steam generated in the boiler decreases. This finally reduces the net power output of the plant. For the same amount of fuel burned, the net power produced by the MSW fired plant reduces to almost half of the net power developed by the coal fired power plant.
2. CO_2 and SO_2 emissions from the MSW fired power plant are less compared to that of the coal fired plant. Low carbon and sulphur content of MSW helps in reduction of these two emissions.
3. The net power output of the topping VPC reduces with increase in CL due to increase in the CT side pumping power requirement.
4. VARS COP is not affected by CL variation, while the component heat loads and the mass flow rates increase proportionately with increase in CL. VARS performance is also independent of the boiler fuels of the topping VPC.
5. With a flue gas temperature of 300ºC at VARS generator inlet, it is possible to achieve cooling more than 2500 TOR as the flue gas temperature at generator exit for the coal and MSW fired plant are still higher than 120ºC.
6. With a flue gas temperature of 150ºC at generator inlet, the steam generation and net power production from the VPC increases while the generator irreversibility decreases; however the maximum cooling that can be achieved is 1300 TOR in case of the coal fired plant and 600 TOR for the MSW fired plant if

the generator exit flue gas temperature is limited to 120ºC to avoid corrosion of the generator tube materials.

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