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Cool Producing Systems Based on Burning and Gasification of Biomass

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Abstract: This paper introduces utilizing of biomass for production of cool. Two different thermal systems are considered as sources of a driving thermal energy, namely burning and gasification of biomass. Burning of biomass produces a hot water or steam used as a driving heat source for an absorption cycle. The mixture of water and LiBr is considered as an appropriate working medium in absorption systems. Different parameters of the absorption system were tested and compared.

Gasification in an atmospheric fluidized bed reactor connected with a trigeneration unit is considered as another thermal system utilizing primary energy of biomass. The system enables to use together an absorption cooling cycle and a vapor-compressor cooling cycle. Efficiency of both systems are calculated and compared. Parameters of the gasification process were derived from measurements carried out on the experimental gasifier at the Brno University of Technology.

Key-Words: cool production, biomass, gasification, burning, absorption cycle

1 Introduction

The sustainable development is connected with intensive utilizing of renewable sources. It is necessary to involve renewable sources in new applications in all areas to fulfill specified targets. Biomass represents the most important renewable source of energy in the central part of Europe. Biomass sources are primarily utilized for heat production and electricity generation. Another interesting application is a production of cool.

The cool production represents a technology with significant consumption of energy. Majority of cooling systems utilize a vapor-compressor cycle driven by electricity. Second possible way of the cool production is to utilize an absorption cycle technology driven by heat energy from different sources.

Burning of biomass produces a hot water or steam convenient as a driving heat source for an absorption cycle. Electricity can be generated from biomass with utilizing of the Rankine cycle, the ORC cycle or a gasification device and a combustion engine. The gasification-thermal engine system enables to utilize both above mentioned cooling systems together and reach the highest cooling efficiency. The terminal cooling capacity depends on the efficiency of a gasification process and the efficiency of cool generating systems. Vapor-compression cycles provide high COP values for a small temperature difference between an evaporator temperature and a condenser temperature. Increasing of the temperature difference causes decreasing of the COP value. The absorption cycle COP value is not so sensitive to the temperature difference between evaporator and condenser. But there are physical limitations of the working temperature range

2 Boiler – absorption cycle system

Direct burning is the most common biomass transformation process for heat production. Efficiency of a boiler depends on its size and design. Heat released from burning process is used for production of a hot water or steam. Heat production is calculated as

$$P_h = m \times Q_h \times \eta_b, \qquad (1)$$

where m is a mass flow of a feeding fuel with the heating value Q_h and the boiler efficiency η_b.

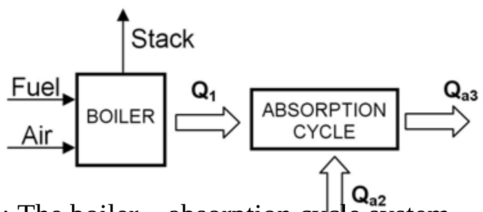

Figure 1: The boiler – absorption cycle system

2.1 Absorption cycle description

Heat from a boiler is transported by a hot water to a heat exchanger of an absorption cycle, see figure 1. An absorption cycle consists from a generator, an absorber, a condenser and an evaporator, see figure 2. These parts are connected by pipes for transport of liquid mixtures and vapors. Throttle valves are used for depressurizing of fluid mixtures. A pump enables to pressurize liquid mixture.

The liquid refrigerant evaporates in the evaporator. The heat flux Q_2 is taken away from an evaporator surrounding. The refrigerant vapors are led to the absorber, where the poor liquid mixture absorbs the refrigerant vapors. The absorption heat Q_4 is released during the absorption process. The saturated liquid mixture is transported to the generator operating on a higher-pressure level.

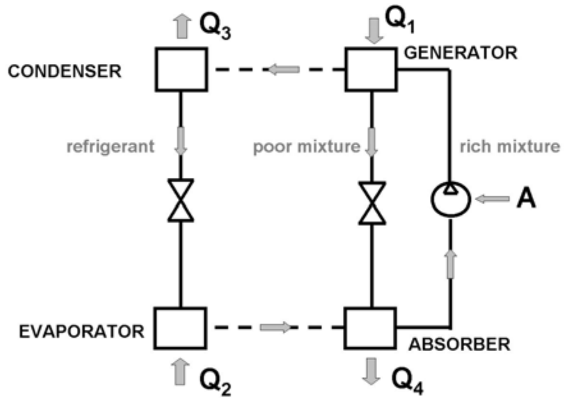

Figure 2: The simple one-stage absorption cycle

The driving heat Q_1 is supplied to the generator by hot water from a boiler. The refrigerant vapors release the mixture during increasing of the mixture temperature. The poor hot mixture returns to the absorber via a throttle valve. The released refrigerant vapors continue to the condenser. The vapors are cooled to lower temperature and condensate to the liquid form. The condensation heat Q_3 is released during this process. Then the liquid refrigerant pass through another throttle valve and enters the evaporator.

The coefficient of performance (COP) evaluates absorption cycle effectiveness.

$$COP = Q_2 / Q_1. \qquad (2)$$

The mixture of water and LiBr is considered as the most frequently used working medium in absorption systems. There is a physical limitation for convenient working temperatures of an absorption cycles [1]. The COP is approximately constant for all variations of convenient temperatures. A higher driving temperature enables to use a the two stage cycle (2°) with a higher COP value. Basic parameters of the one stage and the two stage cycle are written in the table 1.

	1° absorption cycle	2° absorption cycle
Driving temperature	90-120°C	>120°C
Cooling temperature	>5°C	>5°C
COP	0,7	1,2

Table 1: Characteristic parameters of absorption cycles

2.2 Cooling capacity

2.2.1 One stage absorption cycle

The lowest temperature of a hot water leaving a biomass feeded boiler is required at the level 90°C for correct operation of the absorption cycle driven by a hot water. The efficiency of the boiler is assumed $\eta_{b1} = 0.85$ in this case. The appropriate *COP* value is 0.7 [1] for the 1° absorption system. The cooling capacity is calculated as

$$Q_2 = Q_1 \times COP_1. \qquad (3)$$

The temperature of a waste heat water leaving the absorption system is assumed 35°C. Amount of the waste heat Q_3 is calculated from

$$Q_3 = Q_1 \times (1+COP_1). \qquad (4)$$

Then the cooling efficiency η_{c1} is expressed as the ratio of the cooling capacity and the primary energy supplied in biomass.

$$\eta_{c1} = Q_2 / (m \times Q_h) = \eta_{b1} \times COP_1 \qquad (5)$$

In this case, the cooling efficiency is 59,5%.

2.2.2 Two stage absorption cycle

The two stage absorption cycle requires a higher temperature level of the driving energy, namely above 120°C. The driving heat is supplied to the absorption cycle from a pressurized hot water or steam. The efficiency of a boiler is lower in comparison with the one stage absorption case due to a higher temperature of the water leaving a boiler $\eta_{b2} = 0.79$. The coefficient of performance of the two stage absorption cycle is significantly higher (COP_2=1.2) and enables to compensate a complexity of the two stage absorptionc system. The cooling capacity of the two stage absorption cycle is calculated by analogy of (3)

$$Q_2 = Q_1 \times COP_2 \qquad (6)$$

and the cooling efficiency η_{c2} is calculated as

$$\eta_{c1} = \eta_{b2} \times COP_2. \qquad (7)$$

The cooling efficiency of the two stage absorption cycle is 94,8%.

2.2.3 Combination of one stage and two stage absorption cycles

A combination of both above mentioned absorption cycles can be used for increasing of the boiler efficiency and reaching the peak cooling capacity. The total boiler efficiency is same as for the one stage absorption cycle application $\eta_{b12} = 85\%$. The boiler efficiency η_{b2} = 79% is connected with the two stage absorption cycle operation and additional η_{b3} = 6% is utilized by the one stage absorption cycle. The total cooling capacity is then

$$Q_2 = m \times Q_h \times (\eta_{b3} \times COP_2 + \eta_{b3} \times COP_1) \qquad (8)$$

and the cooling efficiency is expressed as

$$\eta_{c12} = \eta_{b2} \times COP_2 + \eta_{b3} \times COP_1. \qquad (9)$$

The cooling efficiency of this complex absorption system is 99%.

3 Gasifier – absorption cycle and vapor cycle system

Gasification is another possible way of energy effective utilizing of biomass. The process of cool production from biomass is realized in tree following steps. First, a low heating value gas (LHV gas) is produced in a gasifier fed by biomass. Second, the LHV gas serves as fuel for a cogeneration unit reprezented by a stroke engine, a gas turbine, the Rankine Cycle or the Organic Rankine Cycle. A cogeneration unit produces heat Q_1 and electricity E in the ratio given by the thermal efficiency of a particular thermal engine. Heat from cogeneration unit and a gasifier is used as the driving energy for an absorption cycle and electricity can power a vapor cycle, see figure 3.

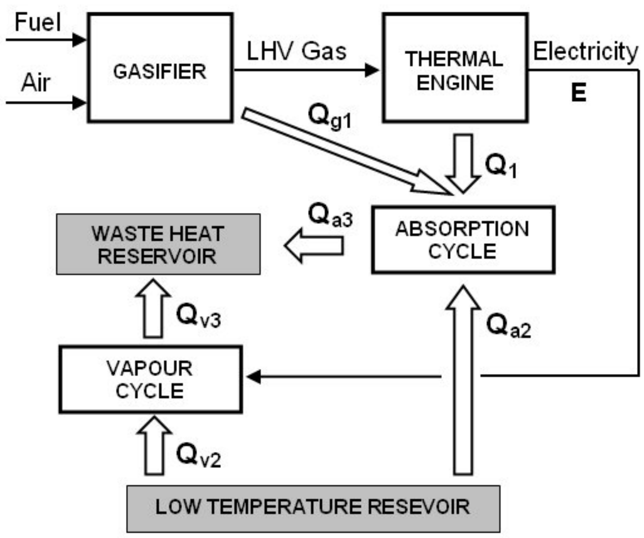

Figure 3: The production of cool based on an atmospheric gasification of biomass

3.1 Experimental fluidized bed gasifier

Parameters describing a gasification process were derived from measurements carried out on an experimental gasifier at the Brno University of Technology. The experimental gasification unit BIOFLUID 100 is convenient for gasification of biomass and solid wastes in an atmospheric fluidized bed. The fuel consumption of the gasifier is 40 kg of wood chips per hour (the heating value 15 MJ/kg). The heating value of the produced LHV gas is Q_{hg} = 4.5 MJ/m_N^3. One kilogram of wood chips produces 2.28 m_N^3 of the gas. Then, the corresponding volume of the gas is calculated as

$$V = 2.28 \times m \, . \quad [m_N^3] \qquad (10)$$

The efficiency of gasification η_g can be expressed as the efficiency of transformation of the wood heating value in the heating value of the appropriate volume of the produced gas with the same temperature. This efficiency of gasification was calculated from the derived data set as 68.5%. A mathematical formulation of the efficiency of gasification has form

$$\eta_g = (m \times Q_h) / (V \times Q_{hg}) \, . \qquad (11)$$

The generated gas outlet temperature is approximately 500°C. The gas sensitive heat Q_{g1} can be used as a driving heat for an absorption cycle (see fig. 3). Amount of the sensitive heat convenient for utilizing in an absorption cycle is approximately 12% of the LHV gas heating value.

Cleaning of the LHV gas leaving a gasifier is necessary for following utilizing of the LHV gas in small-scale CHP units with a stroke engine. It is necessary to remove mainly solid particles and tars.

3.2 Cooling capacity

3.2.1 Without utilizing of sensitive heat of LHV gas

The temperate of water cooling a stroke engine is commonly close to 90°C. From this reason, only the one stage absorption cycle can be engaged for utilizing of the heat from a stroke engine. The cooling capacity of this system is strongly dependent on the vapor cycle efficiency. That is directly connected with the thermal efficiency η_t of a used thermal engine. Different types of a thermal engine can be used with the thermal efficiency in the range 0.1 to 0.5, namely the Rankine Cycle, the Organic Rankine Cycle, the Stirling engine, a stroke engine and a gas turbine. A stroke engine is the most common thermal engine applied at these applications. A higher thermal efficiency results in higher production of electricity and a lower heat flux released from the thermal engine. It is impossible to utilize the entire heat released by a thermal engine. We assume the thermal engine heat loss ξ = 10% from the thermal engine incoming energy. At this case we consider only the heat from a thermal engine Q_1 as the driving energy of an absorption cycle. Utilizing of the sensitive heat of the gas Q_{g1} is neglected in this case.

The cooling capacity of a absorption cycle is calculated as

$$Q_{a2} = V \times Q_{hg} \times (1 - \eta_t) \times (1 - \xi) \times COP, \quad (12)$$

where V is volume of the LHV gas with the heating value Q_{hg}. A thermal engine operates with the thermal efficiency η_t and the engine heat loss ξ. The COP is the coefficient of performance of an absorption cycle.

The cooling capacity of the vapor cycle can be expressed as

$$Q_{v2} = V \times Q_{hg} \times \eta_t \times \varepsilon_c, \quad (13)$$

where ε_c is the cooling factor of the vapor cycle expressed as

$$\varepsilon_c = (T_2 \times \eta_p) / (T_3 - T_2). \quad (14)$$

T_2 and T_3 are respectively the temperature of a low temperature reservoir and the temperature of a waste heat reservoir expressed in the Kelvin. The efficiency of compression η_p strongly influences cooling capacity of the vapor cycle due to significant changes of the cooling factor value.

The total cooling capacity of the entire system is a sum of partial cooling capacities (12) and (13).

$$Q_2 = Q_{a2} + Q_{v2} \quad (15)$$

The entire cooling efficiency of the system η_c is then expressed as

$$\eta_c = \eta_g \times (\eta_t \times \varepsilon_c + (1 - \xi) \times (1 - \eta_t) \times COP) . \quad (16)$$

3.2.2 With utilizing of sensitive heat of LHV gas

The sensitive heat of the LHV gas can be used as an additional driving heat for an absorption cycle. Its utilizing increases the cooling capacity of the absorption cycle and improves the entire cooling efficiency of the system. The vapor cycle is not influenced by this additional heat source and equations (13), (14) and (15) stay valid.

The cooling capacity of the absorption cycle is in this case calculated as

$$Q_{a2} = (V \times Q_{hg} \times (1 - \eta_t) \times (1 - \xi) + Q_{g1}) \times COP. \quad (17)$$

The entire cooling efficiency of the system η_c is now

$$\eta_c = \eta_g\times(\eta_t\times\varepsilon_c+COP(\eta_{g1}+(1-\xi)\times(1-\eta_t))), \quad (18)$$

where $\eta_{g1} = Q_{g1} / (V \times Q_{hg}). \quad (19)$

4 Results and discussion

A mathematical solution of the above mentioned equations was used for expression of the influence of particular parameters on the cooling capacity of the system. For fast comparison of the entire process, the cooling capacity obtained with utilizing of 1 kg of wood (15MJ/kg) is expressed and compared.

The cooling capacity of the boiler–absorption cycle system was calculated for the one stage absorption cycle (3), the two stage absorption cycle (6) and the combination of both cycles (8). Obtained results are graphically expressed in figure 4. The single stage absorption cycle is capable to operate with the cooling capacity 2.48 kWh per kg of biomass. The two stage absorption cycle provides significantly higher cooling capacity 3.95 kWh per kg of biomass. The combination of both cycles provides the highest cooling capacity 4.13 kWh per kg of biomass.

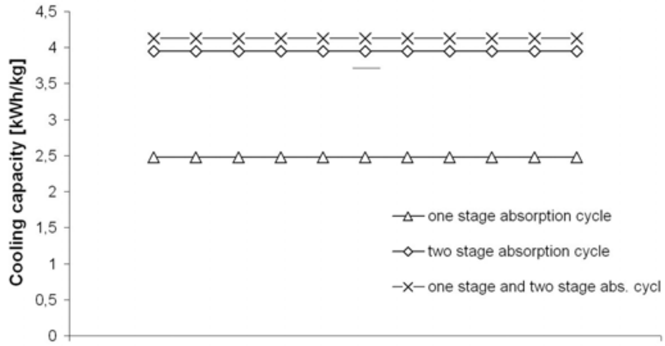

Figure 4: The cooling capacity of absorption cycles engaged in the boiler–absorption cycle cooling systems

The cooling capacity of the system consisted from a gasifier, an absorption cycle and a vapor cycle is a function of the efficiency of a thermal engine, see fig. 5. Utilizing of the LHV gas sensitive heat improves the cooling capacity. The new cooling capacity values are moved up from previous positions by the distance corresponding to the cooling capacity contribution caused by utilizing of the sensitive heat in an absorption cycle, see fig. 5.

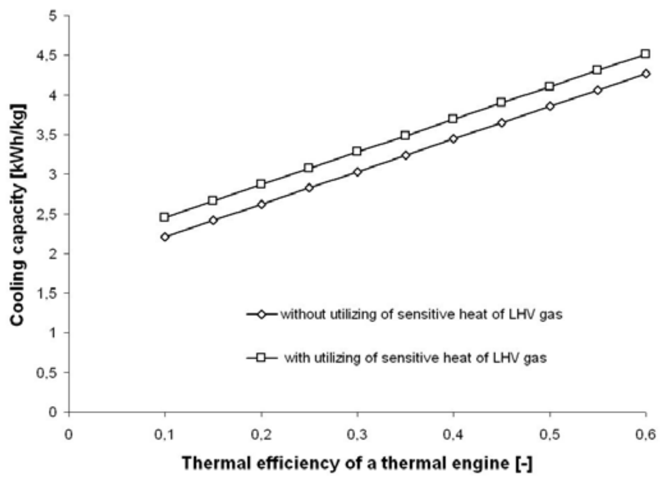

Figure 5: The cooling capacity of the gasifier–absorption–vapor cycle cooling system

The figure 6 shows the relation between the efficiency of a thermal engine and the cooling capacity of a system. The increasing thermal efficiency causes improvement of the cooling capacity.

The vapor cycle efficiency is not influenced only by the efficiency of a thermal engine. Another important parameter significant for the vapor cycle operation is the temperature difference between a low temperature reservoir and a waste heat reservoir. The increasing temperature difference decreases the cooling factor of the vapor cycle. The cooling capacity of the system was calculated for three different temperature differences, namely 20°C, 40°C and 60°C. Figure 6 shows obtained results. Increasing of the temperature difference significantly decrease the cooling capacity of the system.

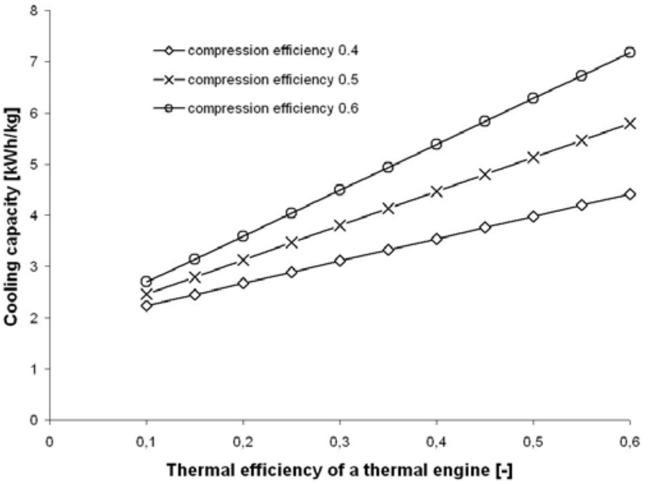

Figure 6: The relation between the thermal engine efficiency and the cooling capacity of the system

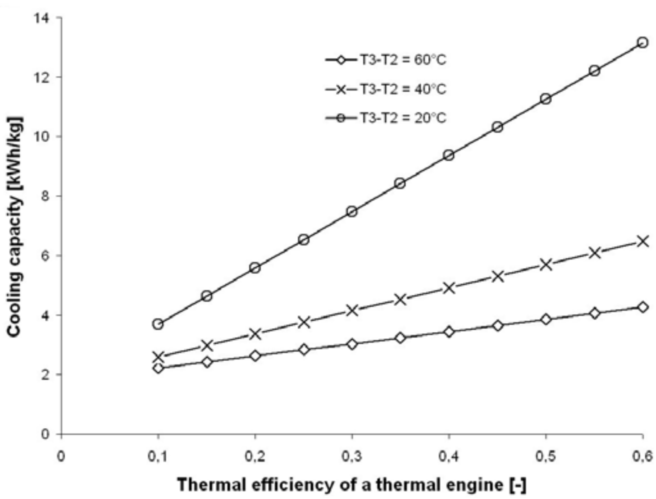

Figure 7: The relation between the temperature difference T_3-T_2 and the cooling capacity of the system

Different operating parameters influence the cooling efficiency of the entire systems. It is important to compare the boiler-absorption cooling system with the gasifier-absorbtion-vapor cycle system with the same operation parameters. The compression efficiency was assumed 0.5 for all compared cases. Two border temperature differences were considered for the gasifier-absorbtion-vapor cycle system.

The figure 8 shows result of the comparison. The temperature difference between the low temperature reservoir and the waste heat reservoir seams to be the most important parameter influencing an election of the convenient cooling system. If the temperature difference is 20°C, the gasifier-absorbtion-vapor cycle system provides better efficiency in comparison with other systems. If the temperature difference is 60°C, the cooling capacity of the gasifier-absorbtion-vapor cycle system is higher than the cooling capacity of the boiler-1°absorption system, but lower than cooling capacity of the boiler-2°absorption system.

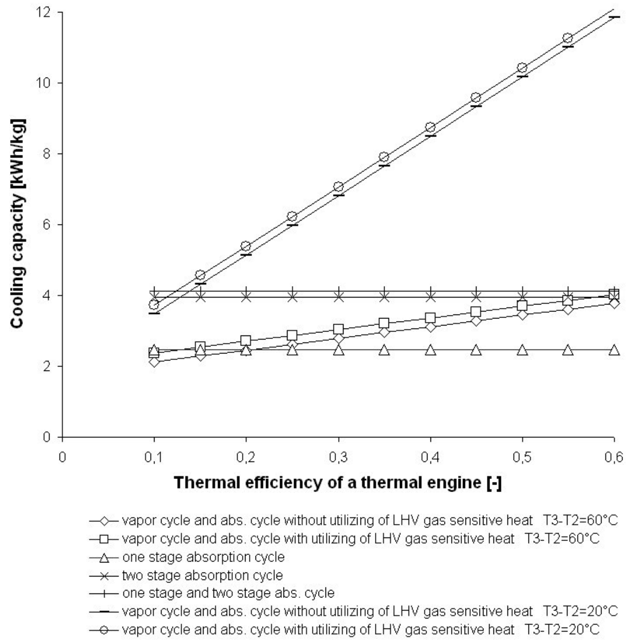

Figure 8: Cooling capacity of systems with different operating parameters

5 Conclusion

In this paper two different thermal systems utilizing biomass for production of cool were compared, namely the boiler-absorption cycle system and the gasifier-absorption-vapor cycle system. Influence of different parameters on the entire system cooling capacity was tested and compared.

The boiler-1° absorption cycle system provides the lowest cooling capacity from all tested systems. The boiler-2° absorption cycle system is convenient for applications with great temperature difference between the low temperature reservoir and the waste heat reservoir. Good thermal efficiency of a thermal engine and high compression efficiency of the vapor cycle is necessary for reaching the peak cooling efficiency of the gasifier-absorbtion-vapor cycle system. The efficiency of a thermal engine is important parameter linearly increasing the cooling capacity of the systems.

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