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Abstract

A room-cooling system of 2 kW capacity fueled by wood pellets was designed, built and tested. The system was demonstrated during summer at the Yakushima Field Station of Kagoshima University, Japan. It contained a pellet feeder, a pellet burner, a heat exchanger, a lithium bromide–water absorption heat pump and a control unit. The volume of the test room was 36.9 m^3 and ambient temperature 30 °C. The airflow temperature from the room unit was decreased to 16 °C by the system, and the room temperature could be successfully controlled to 24 °C steady state. Room heating in winter was also demonstrated. Since the air was heat exchanged, the overall energy efficiency of the cooling system was low at about 19%. However, the calculation based on the heat flow showed that the efficiency could be enhanced to about 75% by direct heating of the regenerator by the flue gas.

Keywords: Wood pellets; Space cooling; Wood chips; Absorption heat pump

1. Introduction

Wood process residues such as sawdust, planer shavings or bark, can be converted to wood pellets by crushing and compression [1]. The use of wood pellets as a renewable energy for residential heating has increased rapidly during the past years in forested countries [2] such as Sweden [3], [4] and [5]. Pellets are one of the most promising alternatives for central heating boilers and stoves in domestic houses, small industrial buildings, agriculture, etc. They are made from by-products of forests or the sawmill industry; the impact to the environment is insignificant as they are carbon neutral.

When the woody biomass feedstock is compressed, the lignin is melted by the generated heat and works as an adhesive agent. Therefore, petrochemical materials are not necessary for the process of pellet production. Their shape is almost uniform and the moisture content is constant between 7% and 15% (dry basis) [1]. Wood pellets have high-energy density up to 18 MJ/kg and are easy to handle when they are transported and stored. The pellets stored in a hopper can be supplied automatically to the burner and the feeding rate is controllable. The heating power of pellet boilers is usually in the range of 10–40 kW [6].

In northern parts of Japan, wood pellets are one of the promising alternatives to fossil fuels for space heating. On the other hand, in southern parts of Japan, which are dominated by warm and humid weather conditions, the requirement for cooling is larger than that of heating. The demand for space heating is relatively small even in winter. Therefore, a cooling system fueled by wood pellets was operated to study the feasibility of a wood-pellet hopper, pellet burner, heat exchanger, cooling unit and control units. The cooling unit utilized a lithium bromide–water absorption system usually directly powered by natural gas, while vapor -compression systems require electrical energy. In addition, the absorption system does not use CFC- or HCFC-based refrigerants [7].

Extending pellet use could introduce large-scale production and decrease production costs. The purpose of the study is to demonstrate a cooling system based on the absorption powered by the combustion of wood pellets and to evaluate the performance of the system based on experimental data, and to demonstrate space heating in winter time.

2. Experimental

The cooling system used for the experiments is shown in Fig. 1. The system was mainly composed of five parts described above. The pellet burner and heat exchanger were manufactured by Kyusyu Olympia Industry Co. Ltd. (Miyazaki, Japan).

The pellets were fed to the burner automatically at a constant feed rate of 9.0 kg h^{-1}. The heat exchanger was installed in the furnace and fresh air was supplied to it without preheating. The flow rate of the air was 57 Nm^3 h^{-1}. The hot air was used for heating the lithium bromide–water solution in the absorption unit and was discharged from the system.

The commercial pellets were obtained from SÅBI Pellets AB, Sweden. They were 8 mm in diameter, 10–30 mm long, density 650 kg m^{-3} and energy content (LHV) 4.9 kWh kg^{-1}. The energy generated by combustion was calculated to be 44 kW. Exhaust gas from the furnace contained 18% H_2O and 7.8% oxygen, but was not utilized for heat recovery in this system and was discharged from the furnace to the atmosphere after ashes were separated by a cyclone.

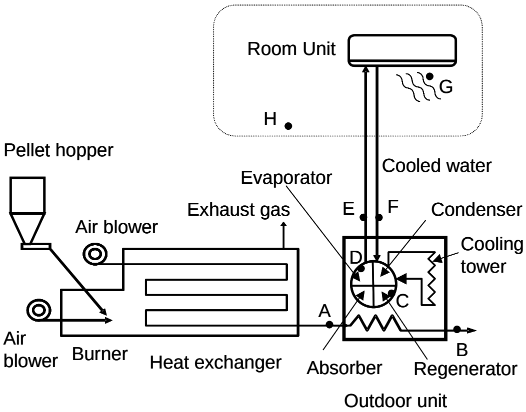

Fig. 1. Cooling system fueled by wood pellets.

An absorption heat pump system was used for cooling. The direct-fired (natural gas) lithium bromide–water absorption machine is a small, gas fired and developed by Rinnai Co., Ltd. (Nagoya, Japan) and Osaka Gas Co. Ltd. (Osaka, Japan) with many technological breakthroughs [8]. The capacity was 2 kW for the room unit and 5 kW for the outdoor unit. A gas burner was removed from the outdoor unit and a pipe installed from the heat exchanger. Basically an absorption system consists of an absorber, regenerator, condenser and evaporator [9] and [10] as shown in Fig. 2. The working fluid is a binary solution consisting of refrigerant (water) and absorbent (lithium bromide). In the evaporator, the water from the room unit is cooled by the heat of vaporization of the refrigerant from the condenser. The vapor flows to the absorber where it is absorbed. The solution is pumped to the regenerator and boiled by the hot air supplied from the heat exchanger. The concentrated solution is returned to the absorber and the vapor flows to the condenser. In the condenser, heat is rejected as the refrigerant condenses, and is removed by the circulating water, which is cooled in a cooling tower.

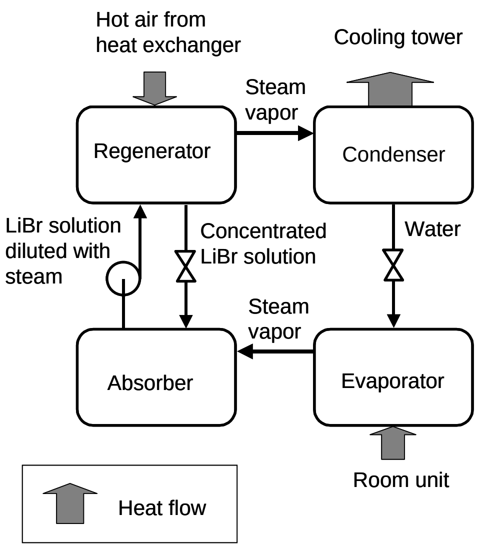

Fig. 2. Main components of the absorption system and heat flows.

The cooling system was demonstrated at the Yakushima Field Station of Kagoshima University in August and September 2003 on Yakushima Island located 60 km from the southernmost tip of Kyushu, Japan. The average daytime temperature in August was over 30 °C. The demonstrations were carried out in rooms on the first floor, although the building has three floors. The area of one room was 17.2 m^2 and height 2.15 m giving a volume of 36.9 m^3. The volume of the other room is similar at 37.3 m^3. Two experimental runs were carried out in each room. Since similar results were obtained, the data from one experiment is described in this paper. Only the room unit was installed in the room and the other units placed outside. The pipes to circulate the cooled water connected the room unit with outdoor unit.

3. Results and discussion

3.1. Start up of operation

It took about 1 h to reach steady-state operation. Fig. 3 shows the change in the temperature on the outer surface of an inlet pipe connected to the outdoor unit of the absorption machine (point A, Fig. 1). The hot air discharged from the heat exchanger flows through this pipe. After 80 s from the start of operation, the burner was ignited and the temperature rose to 254 °C after 30 min. Since the heat exchanger unit was covered by heat insulating material and the heat capacity was large, it took about 1 h for the air temperature to reach 380 °C. The surface temperature of the pipe reached 430 °C at steady state and the temperature of the hot air was about 50 °C higher than this surface temperature.

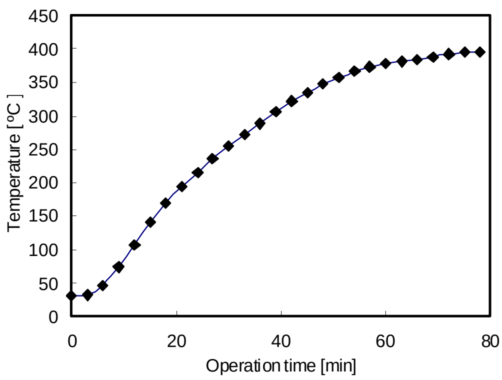

Fig. 3. Temperature change in outer surface of inlet to outdoor unit (point A, Fig. 1).

In a gas absorption system, the lithium bromide–water solution absorbs steam and the solution is diluted (Fig. 2). This solution is heated and concentrated in a regenerator. In the present system, the hot air from the heat exchanger was used for boiling the solution in the regenerator. The temperature of the hot air decreased after heating and was discharged from the outdoor unit. Fig. 4 shows the temperature of the discharged air at the point B in Fig. 1. The temperature of the discharged air was 10 °C lower than the regenerator (point C, Fig. 1), being caused by the heat loss from the pipe between the regenerator and the outlet. A cooling tower in the outdoor unit started working after 12 min, the temperature of the regenerator increased to over 100 °C after 15 min and the temperature of the circulating water began to decrease. The temperature of the regenerator became constant after 50 min.

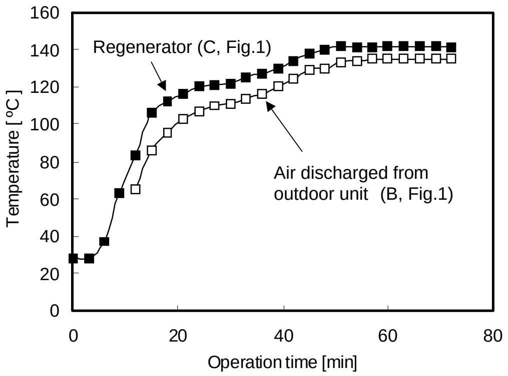

Fig. 4. Temperature change in high-temperature regenerator.

The temperature of circulating water measured at the outlet and inlet from the outdoor unit (points E and F, Fig. 1) decreased with time (Fig. 5). The temperature of cooled water supplied from the outdoor unit increased by the heat exchange in the room unit to cool the airflow. It took about 50 min to reach a steady-state circulation operation. After the temperature of the regenerator (Fig. 4) exceeded 100 °C, the temperature of the circulating water and the evaporator began to decrease. The circulating water existed in the evaporator, in the pipes connecting the two units and in the room unit. This caused the delay observed in the temperature decrease requiring an extra 20 min to cool all the water in the system. The temperature of the evaporator reached 10 °C after 30 min. Since the pressure in the evaporator is very low, the heat is removed from the cool circulating water when vaporization occurs.

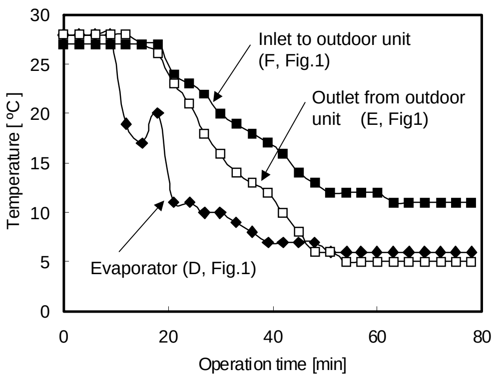

Fig. 5. Temperature change in circulating water to and from outdoor unit.

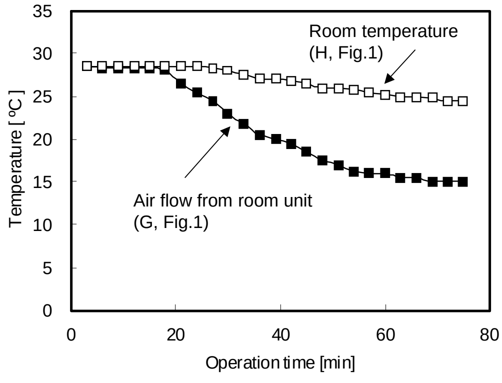

Fig. 6. Change in room temperature.

The room temperature (point G, Fig. 1) was measured at the center of the room. The temperature of the air from the room unit (point F, Fig. 1) began to decrease after 20 min of the start of operation (Fig. 6). This corresponded to a decrease in the temperature change of circulating water shown in Fig. 5. The airflow temperature reached 17 °C after 50 min and the room temperature reached 24 °C after 70 min.

3.2. Steady-state operation

The ambient temperature was 31 °C during the operation, and the room temperature successfully controlled to 24 °C under steady-state operation. Under these conditions, the temperature of the cooled water was about 6 °C and the temperature of the cooled water returning from the room unit was 12 °C. The temperature difference was mainly due to the heat exchanger in the room unit. The heat removed from the air in the room was carried out by this circulating water. In our system, the capacity of the pellet burner was greater than the cooling capacity of the room unit. For that reason, combustion was sometimes interrupted by a signal from a control unit.

3.3. Heat balance

When the original model of the cooling unit utilized natural gas, the cooling capacity of the outdoor unit was 5.0 kW and the rate of energy consumption was 5.33 kW. By assuming that the efficiency of heat transfer in the heating unit was 85%, 4.53 kW of energy flow rate was required for heating the solution in the evaporator.

The heat transfer rate was calculated from the temperature difference between the regenerator and hot air and the airflow rate. The efficiency of heat transfer of the present system was obtained to 77% by dividing the heat transfer rate by the enthalpy flux of the hot air (Appendix A). The maximum temperature of hot air in the system of 510 °C was lower than the temperature generated when natural gas was directly fired for the heating. Therefore, the efficiency was somewhat lower in the case of indirect heating with pellets. Since the aim of the present study was to confirm the successful operation of the cooling system fueled by wood pellets, optimizing the efficiency was not included in the system design.

The energy balance at steady-state operation shown in Fig. 7 was based on the capacity of the outdoor unit. The width of arrow is related to the energy flow. Since 5.91 kW hot air was required from the pellet burner to obtain a cooling capacity of 5.0 kW, the suitable capacity of the pellet burner at 22% efficiency was calculated to be 26.5 kW. Since the consumption of electricity was 0.45 kW, the value of coefficient of performance (COP) of the total system was 0.19 (Appendix B).

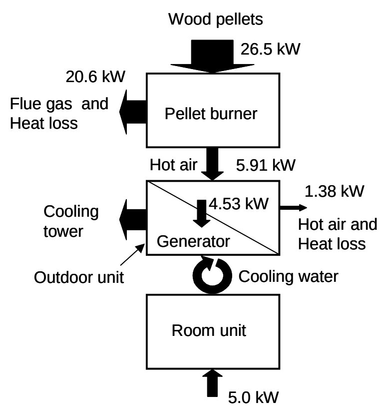

Fig. 7. Energy flow for the cooling system of 5 kW capacity.

The efficiency will be increased by returning the hot air from the outdoor unit to the inlet of the heat exchanger to decrease the energy demand for air heating (Fig. 8). The capacity of the pellet burner can be reduced to 21.0 kW by heating the hot air discharged at 130 °C (point B, Fig. 1) in the heat exchanger instead of fresh air at 30 °C. The COP value slightly increased to 0.23 (Appendix C).

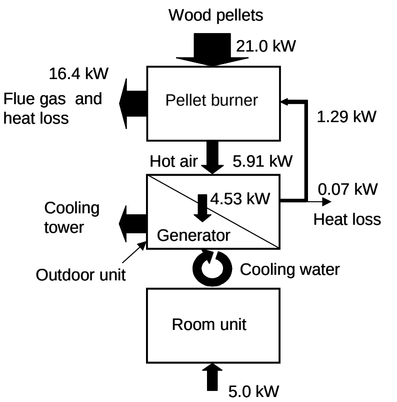

Fig. 8. Energy flow in the system with hot air recirculation.

To obtain the maximum efficiency of the cooling system, it is possible to heat the regenerator by the flue gas directly giving an overall efficiency that is almost the same as a natural gas-fired system. The energy balance of this system is shown in Fig. 9. The required capacity of the pellet burner is 6.22 kW by assuming that the heat loss at a wood-pellet combustor is 5%. The COP value of the total system, including the consumption of electricity, was 0.75 (Appendix D).

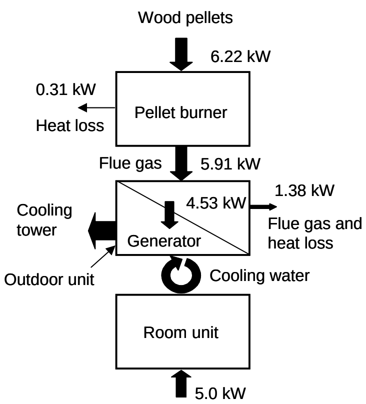

Fig. 9. Energy flow in the system with direct firing.

3.4. Space heating

A demonstration of space heating was carried out in December. Since the exhaust gas from the pellet burner contained a large amount of carbon dioxide, it could not be directly used for space heating. Therefore, heat-exchanged fresh air was diluted and supplied to the room. The ambient temperature was 12 °C during the test. The temperature of air supplied to the room was 87 °C when it was measured at the outlet.

When the heating capacity was 1.3 kW, the room was kept above 24 °C at steady-state operation. The system had a heating capacity of 9.8 kW at full power operation as shown in Fig. 10. Therefore, it would be suitable for heating a room up to 30 m^2 even in a cold district. Heat generation by pellet combustion was 44 kW with efficiency about 0.22, lower than that of commercial pellet stoves about 0.8 because the system was not designed as a heating device. The heat exchanger produced air above 400 °C. If the required maximum air temperature is 50 °C, the efficiency would be increased to a similar level as commercial stoves.

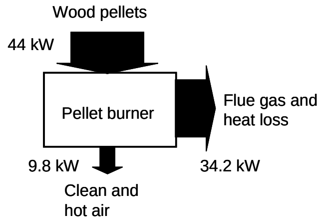

Fig. 10. Energy flow in the case of room heating.

4. Conclusions

A room-cooling unit fueled by wood pellets based on the technology of a lithium bromide–water absorption heat pump was demonstrated successfully. At steady-state operation, the room temperature was controlled to 24 °C when the ambient temperature was 30 °C. The overall energy efficiency of this system was very low at about 0.19. However, the calculation based on heat flow showed that the efficiency could be enhanced to about 0.75 by heating the regenerator by the flue gas directly.

Acknowledgments

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Appendix A. Efficiency of heat transfer

The fresh air of 30 °C was heated to 510 °C by the heat exchanger. The enthalpy change is calculated by the product of mass flow rate of the air, heat capacity and temperature difference. Assuming that the temperature of the hot air decreased to 142 °C (the temperature of the regenerator), and that the molar heat capacity was constant, the ratio of energy transferred from hot air to the regenerator was calculated by (510–142)/(510–30) to be 0.77.

Appendix B. COP of the present system

The total energy input was the sum of electricity consumption and the heat input from wood pellets. The COP is determined from the ratio of the evaporator load and the total energy input:

$$COP=5.0/(0.45+26.5)=0.19.$$

Appendix C. COP for the system with hot air recirculation

In the case of hot air recirculation, the air of 130 °C is heated by the heat exchanger. Since the ratio of the temperature difference is (510–130)/(510–30)=0.79, the required energy is 21.0 kW (79% of 26.5 kW), therefore

$$COP=5.0/(0.45+21.0)=0.23.$$

Appendix D. COP for the system with direct heating

$$COP=5.0/(0.45+6.22)=0.75.$$

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