Proceedings of POWER2008
ASME Power 2008
July 22-24, 2008, Orlando, Florida, USA

POWER2008-60164

A NEW RE-FUEL SYSTEM TO PROCESS HIGH WATER CONTENT WASTE TO SOLID FUEL USING SUPERHEATED STEAM

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ABSTRACT:
The increase of waste and the dryness of natural resources including fossil fuels have become serious problems for the sustainable development of industrial activities and our daily living. A great deal of human effort has been put into the careful use of finite resources and environmental impact reduction. The appropriate processing and the effective use of waste are really in demand in light of our social responsibility for manufacturing and energy development. In addition, the construction of a new recycle system for production is also important from the standpoint of the manufacturer's responsibility. A procedure is being developed to process industrial and municipal wet wastes to solid fuel, called Refuse paper & plastic fuel (RPF), using superheated steam. A drying system using superheated steam is drawing much attention for use with drying high water content materials due to its high thermal efficiency. A material recycle system for processing high water content waste to solid fuel will be introduced in the present study using a demonstration system, and the optimum conditions for the system operation will be examined. The temperature and the quantity of superheated steam required for material drying are evaluated, and the energy consumption and emissions from the system are theoretically estimated and compared.

The purpose of this paper is to test-operate a practical waste recycle system, and the results of this new system are compared with the results from a waste incinerator. The effectiveness of a drying system using superheated steam is shown from the standpoint of the reduction of CO_2 emissions and energy consumption for the waste processing.

INTRODUCTION

Air pollution and global warming based on fossil fuel burning and enormous refuse disposal have become serious problems. The drastic increase in world population and the economic growth of developing countries affect the increase of industrial and municipal wastes, and depletion of natural resources. Especially, high water content waste, such as leftover food and sludge, requires additional fuel to assist incineration disposal. In general, heavy oil is used as a supplementary fuel, which emits CO_2, pollutants etc. Much supplementary fuel and electricity will be required to process waste. As a result, CO_2 and pollutants emitted from fossil fuels are added to the emissions from the waste. In addition, landfill sites will be diminished in the near future. Therefore, almost all waste is either incinerated or buried in point of fact.

Recently, one procedure is being developed to process the industrial and municipal wastes to solid fuel, called Refuse paper & plastic fuel (RPF), using superheated steam. A drying system using superheated steam is drawing much attention for use with drying high water content materials due to its high thermal efficiency[1-6]. A superheated steam is a gas made by heating saturated steam to more than the boiling point. This drying system is very useful for the processing of high water content waste. However, the temperature and the quantity of superheated steam required for material drying have not been clearly determined. This is very important for drying with high efficiency.

In this study, this drying system is applied to high water content waste such as used solid paper diaper, which is then processed into solid fuel RPF. In this paper, a material recycle system for processing high water content waste to solid fuel will be introduced using a demonstration system, and the optimum conditions for the system operation will be examined. The temperature and the quantity of superheated steam required for waste drying are evaluated, and the energy consumption and emissions from the system are estimated and compared. In addition, the environmental and thermal advantages of this waste recycle system are compared with the conventional incinerator.

SUPERHEATED STEAM DRYING SYSTEM

Characteristics of superheated steam

Superheated steam is an atmospheric steam heated to around 100 deg-C or more. The gas has a high specific enthalpy compared with hot air at the same temperature. The superheated steam promotes the drying of water content materials by convection, radiation and condensation heat transfers. The condensation heat transfer is a special feature of a superheated steam drying system, which a hot air drying system does not have. When the surface temperature of the material is lower than 100 deg-C, superheated steam can give a large amount of condensation heat to the material. So far, the superheated steam drying system has been developed and applied to food processing, wood processing and carbonization of wastes.

The steam has the following characteristic advantages especially for waste processing: a) Inactive gas: When the drying chamber is filled with the superheated steam, a chemical reaction such as ignition can be prevented since the vapor does not contain O_2. There is no fire or explosion in the drying apparatus, thus assuring safety in the waste disposal process. b) High heat capacity: Superheated steam has several times the heat capacity as high temperature air. This means shorter working hours and high thermal efficiency. In addition, the gas has useful features for waste disposal including sterilization, degreasing and deodorizing.

Drying theory of wet material

A wet material is processed in an open-type drying chamber, where the superheated steam and the material flows in a parallel direction as shown in Figure 1. The material is dried by heat exchange between the steam and the material[7,8]. The drying theory to estimate the mass flow rate of superheated steam is shown in this paper.

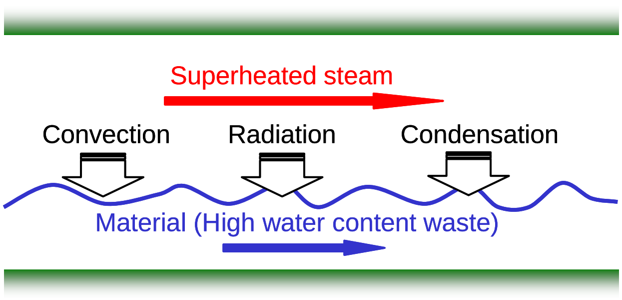


Figure 1
Superheated steam and material flow in an open-type drying chamber.

The heat flow rate of the superheated steam, $\dot{Q}_{st}$, supplied to the drying chamber is expressed by the following equation.

$$\dot{Q}_{st} = \dot{Q}_d + \dot{Q}_{loss} \qquad (1)$$

where $\dot{Q}_d$ is the heat required for the drying of the wet waste and $\dot{Q}_{loss}$ is the heat loss that passes through the drying chamber wall. The mass $\dot{m}_{waste}$ of wet material passes through the drying chamber per unit time. The material is considered to consist of dried solid and water components. The heat of the wet material, $\dot{Q}_{waste,1}$, per unit time at the inlet temperature, $T_{waste,1}$, based on the reference temperature, T_0, can be calculated as:

$$\dot{Q}_{waste,1} = \dot{m}_{waste}\{w_b c_w + (1-w_b)c_{so}\}(T_{waste,1} - T_0) \qquad (2)$$

where c_w, c_{so} and w_b are the specific heat of water, the specific heat of dried solid and the ratio of moisture content of the material.

The temperature of water in the waste becomes the same as that of the superheated steam at the exit of the drying chamber. Only the heat amount from the inlet temperature to the temperature increase is taken into account for the solid component. Therefore, the heat required for the drying of the wet waste is obtained as:

$$\dot{Q}_d = \dot{m}_{waste}\left[w_b\{h_2 - c_w(T_{waste,1} - T_0)\} + (1-w_b)c_{so}(T_2 - T_{waste,1})\right] \qquad (3)$$

where T_2 and h_2 are the temperature and the enthalpy, respectively, of the superheated steam at the exit of the drying chamber. Then the mass flow rate of the superheated steam is obtained as:

$$\dot{m}_{st,1} = \dot{Q}_{st} / (h_1 - h_2) \quad (4)$$

where, h_1 is the enthalpy of the superheated steam in the drying chamber at the inlet temperature. The enthalpy h_1 and h_2 can be readily obtained from the steam table based on the respective pressure and temperature.

Experimental setup and method

Figures 2 and 3 show the respective layout and a photo of the superheated steam drying system employed in this experiment. The designed process capacity of the wet waste is 400 kg-waste/h.

The steam generated by the auxiliary boiler flows into the heat exchanger, where the high temperature gas is supplied from the hot gas generator, and the steam is then superheated. The steam is supplied from the auxiliary boiler only in the beginning of system operation. The superheated steam enters the multistage drying chamber, and the waste is supplied to the drying chamber after it passes through a crusher to be a suitable size for the drying in order to promote drying efficiency. The steam dries the waste by convection, radiation and condensation heat transfers. The dried material is discharged from the drying chamber at less than 170 deg-C in order to prevent ignition, and compressed by a granulator. The solid material called RPF is shown in Figure 3. The steam, together with the moisture from waste, circulates through this system. The mass of the steam at the exit of the drying chamber increases by the moisture originating in the waste. The steam passes through a dust extractor to remove its dust, and then the steam is separated into the main and surplus flows. The steam of the main flow is introduced into the heat exchanger by a blower and circulates in the system. The mass flow rate of the steam is estimated by Eq. (4) at the drying chamber inlet. On the other hand, surplus steam passes through the deodorizer, and is pyrolyzed with the hot gas generator and discharged to the atmosphere.

The hot air is supplied to the drying chamber before the waste is introduced into the chamber. After the chamber is heated to a higher temperature for the evaporation of water, the superheated steam is supplied to the chamber. An oxygen densitometer is introduced into this system to determine the steam concentration, i.e., the displacement of air. After the chamber is filled with the superheated steam, the waste is introduced into the chamber. It takes 2 hours to dry the waste in this system.

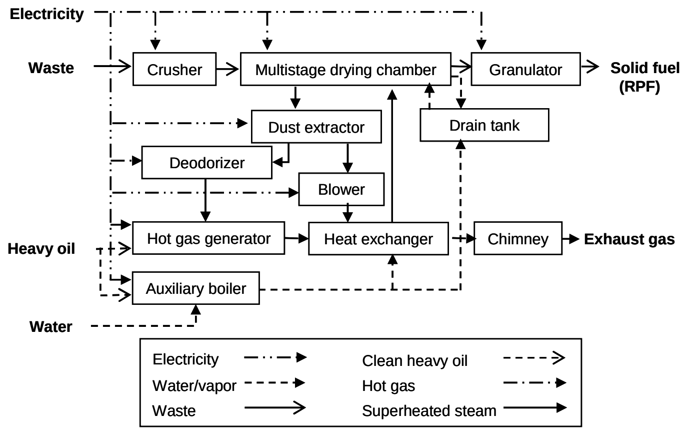
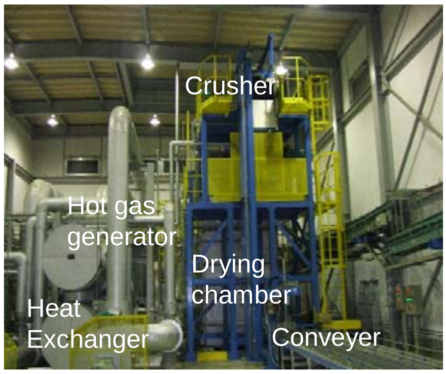


Figure 2
Energy and material flow of superheated steam drying system.



(a) Drying system

(b) Solid fuel (RPF) made from high water content waste

Figure 3
Photo of the superheated steam drying system employed in this experiment.

The mass flow rate of the steam is appropriately controlled by the blower in terms of the condition of waste. Thermocouples are equipped in the hot gas generator, heat exchanger, drying chamber, ducts etc. The flow rate, pressure and temperature of the steam are measured by the flow meter, pressure gauge and thermocouples, respectively. These data are collected and processed by personal computer. After supply of the waste is stopped, the steam is discontinued after 2 hours.

Figure 4 shows the layout of the incinerator employed in this experiment in order to compare the characteristics of two waste processing systems. The designed capacity of the wet waste is 260 kg-waste/h. The waste is supplied to the incinerator by a waste supply unit, and burned. The exhaust gas from the incinerator is burned again in the secondary combustion section in order to control the exhaust gas composition. Then the exhaust gas is cooled by the cooling tower and emitted through the chimney. The mass of waste, temperature inside the incinerator, heavy oil and electricity consumption are measured.

The incinerator is heated by a burner for a short time in order to control the exhaust gas temperature, and then the wet waste is introduced. It takes half to one hour to burn up the waste after the supply of waste is stopped in this system.

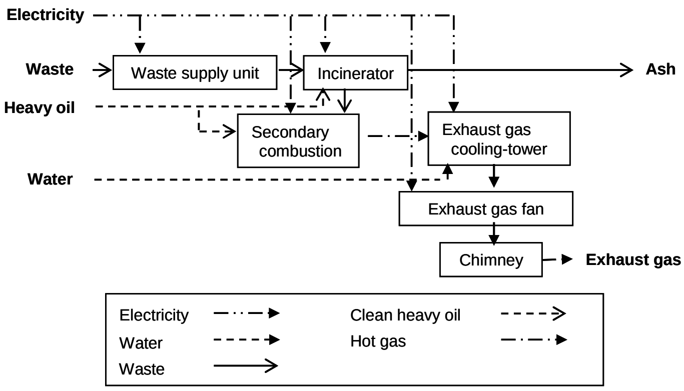


Figure 4 Energy and material flow of incinerator.

Experimental evaluation method

Figure 2 also shows the waste and energy flow of the system employed in this experiment. In the superheated steam drying system, waste, electricity, heavy oil and water are supplied as input, while the solid fuel, that is RPF, is discharged from the chamber as output. Exhaust gas from heavy oil burning is also emitted. Water is used to generate the initial steam in the superheated steam drying system.

On the other hand, in the incinerator, the waste is supplied to the incinerator and burnt to become ash, as shown in Figure 4. The inputs are waste, electricity, heavy oil and water. However, water is used to cool the exhaust gas in this system. Ash and exhaust gas are considered as outputs.

In this evaluation, the heavy oil and electricity supplied to the waste supply unit, incinerator and secondary combustion are taken into account. The electricity required for operation of the cooling tower and exhaust gas fan are not added, because these peripheral devices are introduced only to control the exhaust gas and do not essentially depend on the burning.

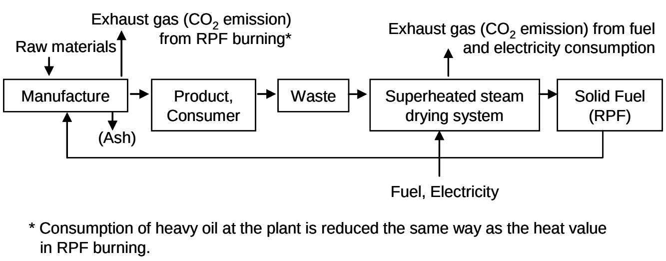
For the environmental assessment of these systems, the mass of waste, fuel consumption, electricity consumption, mass of RPF, exhaust gas composition and temperature are measured. It is very important for the environmental assessment to define the system boundary. Table 1 shows the system boundary of environmental evaluation. It is difficult to incinerate the 75 wt% water content waste in this incinerator, even if supplementary fuel is introduced. Therefore, the cloth and paper waste are mixed to the high water content waste and the average amount of water content is reduced in the incinerator. The schematic flow of environmental evaluation is shown in Figure 5. Only the factors that should be evaluated are indicated in this figure.

Table 1
System boundary of environmental evaluation.

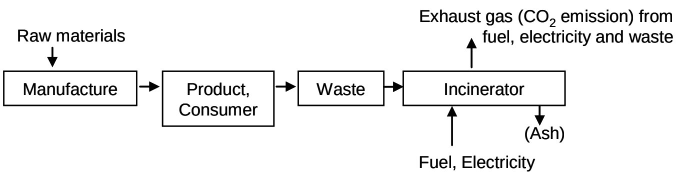
	Superheated steam drying system	Waste incinerator
Input	Waste (75 wt% water content) Fuel (Heavy oil) Electricity	Waste (75 wt% water content) Fuel (Heavy oil) Electricity
Output	Exhaust gas (CO_2 emission) Solid fuel (RPF)	Exhaust gas (CO_2 emission)

In this assessment, the RPF generated from the superheated steam drying system is assumed to be used as a heat source for the manufacture of the original products, as shown in Figure 5(a). The CO_2 emission from the RPF combustion is taken into account in the evaluation. In this case, the consumption of heavy oil at the plant may be reduced the same way as the heat value in RPF burning. Then the CO_2 emission and composition of the heavy oil is reduced. However, the environmental impacts derived from the construction of the equipment and the transportation of RPF are not added, and the thermal efficiency of RPF furnace is set as 1.0.

On the other hand, in the incinerator, fuel and electricity consumptions are taken into account. Then the CO_2 emission from heavy oil, waste and electricity are added.



(a) Superheated steam drying system with fuel recycling

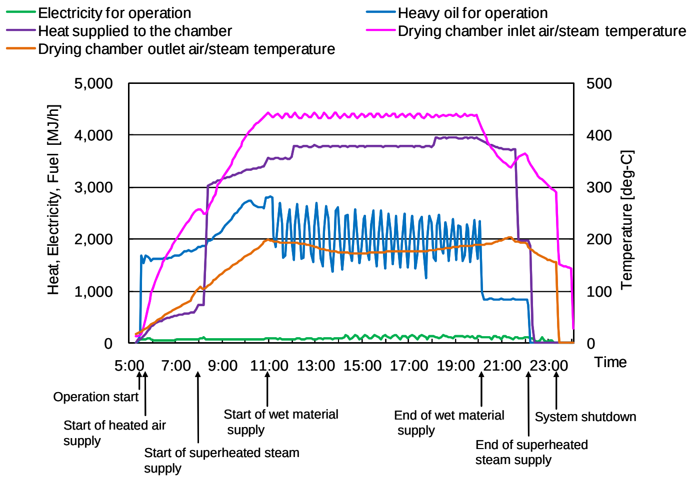


(b) Incinerator

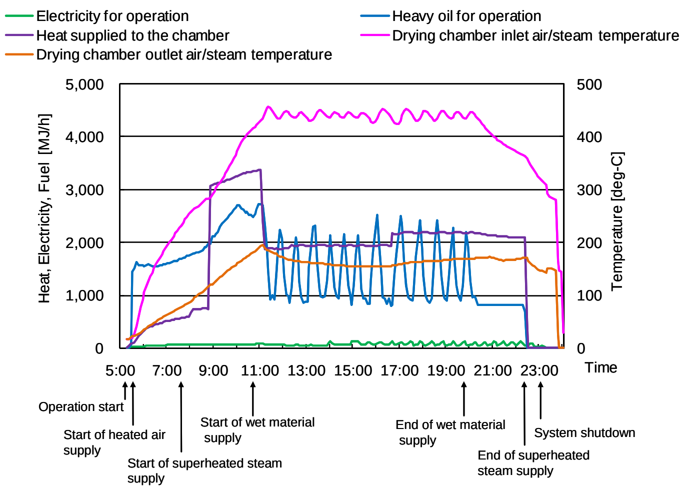
Figure 5
Schematic flow of environmental evaluation.

Experimental result and discussion

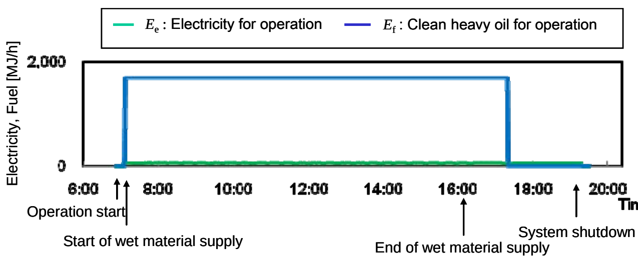
Figure 6 shows the time evolution of the temperature and energy consumption for each system. A used solid disposable paper diaper is processed in this experiment. A huge amount of energy is consumed before and after the waste supply to the drying chamber in the superheated steam drying system, as shown in Figures 6(a) and (b). It takes 5 or 6 hours before supplying the waste to the drying chamber in the drying system, in order to increase the temperature within the chamber to more than the condensing temperature of water. Moreover, 3 or 4 hours are required after supplying the waste. The energy loss and exhaust gas during these periods are significant, as shown in Figures 6(a) and (b). The energy loss in these sections can not be ignored, although it is very small in the incinerator, as shown in Figure 6(c). Thus, it is important for the superheated steam drying system to operate continuously for a long time.



(a) Time evolution of temperature and energy of superheated steam drying system (400 kg-waste/h)



(b) Time evolution of temperature and energy of superheated steam drying system (200 kg-waste/h)



(c) Time evolution of energy of combustion furnace system (260 kg-waste/h)

Figure 6
Time evolution of temperature and energy consumption.

The environmental evaluation is performed based on the data that are obtained in one cycle of operation or are extracted in the steady-state condition from one cycle of operation. At first, the environmental impact of the superheated drying system operated at the designed system value, 400 kg-waste/h, is compared with the result from an incinerator in order to show the advantage and disadvantage of introducing the superheated steam drying system. Then the impact of steady-state operation is evaluated.

Table 2 shows the environmental impact evaluated in a one-cycle operation. The mass of waste is put at 200 and 400 kg-waste/h in the experiment. The numerical value in the waste incinerator is set as unity, and the value estimated from the drying system is shown as a ratio thereof. The experiment is conducted at a rate of 260 kg-waste/h in the incinerator.

In this evaluation, the heat obtained from RPF burning is calculated in the required heat source for the drying. Then the consumption of the heavy oil is reduced considerably in the case of a designed capacity of 400 kg-waste/h. The CO_2 emission coefficients of heavy oil, electricity, RPF and waste are also shown in Table 2. The CO_2 emission coefficient of RPF is measured from the test piece. Then the coefficient of waste is numerically calculated based on the ratio of the waste solid component. If the RPF is supplied as the heat source of the system, the consumption of heavy oil is reduced to 0.67 even though the total energy consumption becomes 1.36, where the heat values of the heavy oil and RPF are defined as 39.1 MJ/L and 19.7 MJ/kg-RPF, respectively. Electricity consumption of the drying system becomes higher than that of the incinerator, because the drying system has a mixing system, a conveyor and a granulator. The CO_2 emission becomes lower than that of the incinerator. The energy estimated from heavy oil and electricity consumption is reduced to 0.71 compared with that of the incinerator, even though the electricity consumption has increased to 1.83. The electricity consumption of the drying system is not significant compared with the fuel consumption. Thus, the total energy consumption is lower than that of the incinerator.

The experimental results obtained by operation with 200 kg-waste/h processing are also shown in Table 2. The ratios in the drying systems are inferior to that of 400 kg-waste/h processing. Power consumption does not depend very much on the mass of waste, because the mixing system, a conveyor and granulator work during the operation continuously. Then the ratio of the electricity consumption becomes high compared with that of the incinerator. The ratio of total energy consumption, heavy oil and electricity becomes over unity. This means that there is no longer any advantage of the superheated steam drying system in this condition, because the mass of waste is quite small compared with that of the designed system capacity. The results will become reasonable when the system capacity is suitably designed for the mass of the waste which must be processed.

Table 2 Comparison of environmental impact by a one-cycle operation.

		unit	Superheated steam drying system + fuel recycle				Waste incinerator	
Waste	processed	kg-waste/h	400		200		260	
	ratio	[-]	1.00		1.00		1.00	
Fuel	heavy oil	MJ	1.36	0.67	2.10	1.46	1.0	1.0
	RPF	MJ		0.69		0.64		-
Electricity consumption		MJ	1.83		2.37		1.0	
CO_2 emission		kg-CO_2/kg-waste	0.87		1.30		1.0	
Energy consumption (Heavy oil + Electricity)		MJ/kg-waste	0.71		1.50		1.0	

* Low heat value of heavy oil: 39.1 MJ/L.
* Low heat value of RPF: 19.7 MJ/kg-RPF.
* Coefficient of CO_2 emission of heavy oil: 0.0693 kg-CO_2/MJ.
* Coefficient of CO_2 emission of electricity (Japan): 0.555 kg-CO_2/kWh.
* Coefficient of CO_2 emission of wet waste (75 wt% water content): 0.45 kg-CO_2/kg-waste.
* Coefficient of CO_2 emission of RPF: 1.8 kg-CO_2/kg-RPF.

Table 3 Comparison of environmental impact by steady-state operation.

		unit	Superheated steam drying system + fuel recycle				Waste incinerator	
Waste	processed	kg-waste/h	400		200		260	
	ratio	[-]	1.00		1.00		1.00	
Fuel	heavy oil	MJ	0.80	0.05	1.17	0.42	1.0	1.0
	RPF	MJ		0.75		0.75		-
Electricity consumption		MJ	1.52		2.09		1.0	
CO_2 emission		kg-CO_2/kg-waste	0.55		0.75		1.0	
Energy consumption (Heavy oil + Electricity)		MJ/kg-waste	0.09		0.47		1.0	

Table 3 shows the results obtained in the steady-state operation in Figure 6(a) and (b). The consumption of heavy oil is reduced considerably compared with that of a one-cycle operation, because the energy required to pre-heat the drying chamber inside and to post-heat the waste after the supply is stopped are not taken into account. The CO_2 emission becomes very low in the fuel recycle system with superheated steam drying system, indicating that continuous operation is very important for high system efficiency.

The advantage of the introduction of superheated steam drying system is clearly shown in this experiment. However, the details such as the energy consumption in transportation, exhaust gas emission and ash should be evaluated in future. In addition, the energy required to construct the system, resource dryness, and production cost should be taken into account for the commercial development.

SUMMARY

The advantages of introducing this new superheated steam drying system to produce a solid fuel from high water content wet waste are shown in this paper. The novel system has special features enabling it to process the wet waste. The energy required to process the wet waste to solid fuel and CO_2 emissions is compared with that of the incinerator. The energy consumption and CO_2 emissions from the drying system are smaller than those of the incinerator, when the solid fuel is used as a heat source. A superheated steam drying system of this kind may be the future of waste processing.

NOMENCLATURE

c = specific heat
h = enthalpy of superheated steam
$\dot{m}$ = mass flow rate
$\dot{Q}$ = heat flow rate
T = temperature
w_b = ratio of moisture content

Subscripts
0 = reference value
1 = value at drying chamber inlet
2 = value at drying chamber outlet
d = drying
loss = loss
so = solid
st = steam
w = water
waste = waste

ACKNOWLEDGMENT
The authors would like to thank Mr. Toshiyuki Takagawa, aada Inc., for his valuable assistance in the experiment and data processing in the present study.

References:

1. **Drying Technology Vol. 12 No. 6, 1994, pp. 1485-1524 -** Steam Drying Technologies: Japanese R & D, H. Shibata and A. S. Mujumdar
2. **Mechanical Engineering Vol. 78 1956, pp. 423-456** - Application of Superheated-Vapor Atmospheres to Drying, A. M. Lane and S. Stern
3. **Drying Technology Vol. 19 No. 7, 2001, pp. 1287-1303 -** Effects of Operational Conditions on Drying Characteristics in Closed Superheated Steam Drying, Y. Tatemoto et al
4. **Trans. ASME J. Heat Transfer Vol. 110 No. 1, 1988, pp. 237-242** - Experimental Measurement of Water Evaporation Rates into Air and Superheated Steam, M. Haji and L. C. Chow
5. **Int. J. Heat Mass Transfer Vol. 26 No. 3, 1983, pp. 373-380 -** Evaporation of Water into a Laminar Stream of Air and Superheated Steam, L. C. Chow and J. N. Chung
6. **Ind. Eng. Chem. Process Des. Develop. Vol. 9 No. 2, 1970, pp. 207-214** - Evaporation of Water in Air, Humid Air, and Superheated Steam, T. Yoshida and T. Hyodo
7. **Proc. of 5th International Energy Conversion Engineering Conference 2007, 2007, Paper No. AIAA 2007-4785** - Material Resource Recycle System from High Water Content Waste to Solid Fuel using Superheated Vapor, N. Maruyama, Y. Ichihashi and D.

Tanaka
8. **Proc. of International Symposium on EcoTopia Science 2007, 2007, Paper No. 25P03-13 -** Environmental Evaluation of Material Resource Recycle System from High Water Content Waste to Solid Fuel using Superheated Steam, N. Maruyama et al