Clean Energy from Gasification of Biomass for Sterilization of Mushroom Growing Substrates

Nakorn Tippayawong, Chutchawan Chaichana, Anucha Promwungkwa, and Presert Rerkkriangkrai

***Abstract*—** Sterilization of mushroom growing substrates is energy intensive process for mushroom cultivation. Fuelwood may be replaced by spent substrates for hot steam generation. However, combustion of spent substrates directly in an open furnace is troublesome due to low efficiency and excessive smoke emission. Alternative conversion of the by-product to provide clean energy should be studied. In this work, recycling of spent mushroom substrates through gasification to provide heat for sterilization of substrate bags has been investigated. The findings showed that spent substrate was successfully used as biorenewable fuel in a gasifier. Satisfactory operation was obtained. Gasification of spent substrate could provide required thermal input, with clean energy to the local mushroom farm. Thermal efficiency of about 20% was achieved, compared to 5% from existing furnace. Preliminary economic analysis showed that the farm can save around $300 a month, with simple payback period to positive cash flow of less than 12 months.

***Keywords*—**Biomass, Efficiency improvement, Mushroom cultivation, Producer gas, Renewable energy, Waste recycling.

I. Introduction

Mushroom growing is increasingly becoming popular in Thailand as a means to generate income, improve quality of life for rural people and promote sustainable development in local communities. Examples of commercially cultivated mushrooms in Thailand are shown in Table 1. Mushrooms are typically grown in wooden logs, compost beds, or biomass substrate bags. Some mushrooms such as oyster, abalone, yanagi and shiitake mushrooms are normally grown in substrate bags [1].

Manuscript received August 14, 2011. This work was supported by the Fund for Energy Conservation Promotion, Thailand's Energy Policy and Planning Office, Ministry of Energy.

N. Tippayawong is with the Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200 Thailand (corresponding author, tel.: +6653944146; fax: +6653944145; e-mail: n.tippayawong@yahoo.com).

C. Chaichana is with the Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200 Thailand (e-mail: c.chaichana@gmail.com).

A. Promwungkwa is with the Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200 Thailand (e-mail: anucha.cmu@gmail.com).

P. Rerkkriangkrai is with the Department of Mechanical Engineering, and the Energy Research and Development Institute Nakornping, Chiang Mai University, Chiang Mai 50200 Thailand (e-mail: prasert.134@gmail.com).

Table 1: Commercial mushrooms in Thailand [1]

Common name (latin name)	Market price ($/kg)*
Oyster mushroom (*Pleurotus ostreatus*)	0.99-1.31
Abalone mushroom (*Pleurotus cystidiosus*)	2.30-2.63
Shiitake (*Lentinula edodes*)	5.25-5.91
Yanagi (*Agrocybe cylindracea*)	8.21-9.85
Parasol mushroom (*Macrolepiota gracilenta*)	13.0-16.5
King oyster mushroom (*Pleurotus eryngii*)	6.57-8.21
Straw mushroom (*Volvariella volvacea*)	2.96-3.94
Button mushroom (*Agaricus bisporus*)	2.63-3.94
Silver ear (*Tremella fuciformis*)	9.85-11.5
Wood ear (*Auricularia auricula*)	0.99-1.64
Reishi (*Ganoderma lucidum*)	33.0-50.0

* ($1.00 = 30.45 Thai Baht, exchange rate on March 2011)

For mushrooms cultivated in bags (Fig. 1), equipments including mixer, bagging machine, compacting machine, steam generator, and sterilizing autoclave are required. Common bag preparation method involves (i) mixing of sawdust, rice bran and gypsum with water content in the range of 60-65%; (ii) filling and compacting the mixtures in the plastic bags; (iii) sterilizing the substrate bags with hot steam at 90-100^{o}C for 3-4 h in a closed autoclave; (iv) cooling down and ready to inoculate with mushroom spawn. Thermal energy is provided from wood burning. This process is energy-intensive, consuming large amount of wood.

Currently, spent mushroom substrates or spent mushroom compost are available in abundance. Environmental concerns have been escalating with regards to its effective recycling and disposal of these wastes. At present, they are discarded on a dumping site in farms, some is burnt as a means for waste management. The burning of these by-products has serious socio-environmental impacts including emissions of greenhouse gases, smoke, and tars, leading to complaints from neighbors. There were attempts to substitute wood fuels by spent substrates. However, direct firing of spent substrates in furnaces, semi open pits, and other open burning application is notoriously poor. Combustion efficiency is low with high smoke emission, and process control is limited. This will bring about more serious air pollution, strengthening greenhouse gas effect, and terrible impact on human health.

Fig. 1: typical mushroom growing in substrate bags

Alternative utilization method is therefore needed for spent mushroom substrates. It has been suggested that they could possibly be used as fuels, feedstock for chemical synthesis, growing media for other plants, soil conditioners, or animal feeds. Examples of these methods may be found in [2-14].

Among many recycling methods, its use as renewable fuels seems to be reasonable and promising. Other thermal conversion of spent mushroom substrates to energy may be employed. Gasification [15, 16] offers optional conversion technology for the biomass residues available that has high thermal efficiency and environmental acceptability. Gasification is a thermochemical processing of a solid into a fuel gas known as producer gas. The process produces combustible gases like CO, H_2 and HCs, from the following reactions [17];

Gasification:

$$\text{Biomass} \rightarrow \text{char} + \text{tar} + \text{gases} \ (H_2, CO, CO_2, CH_4) \quad (1)$$

Thermal decomposition:

$$\text{tar} \rightarrow \text{gases} \ (H_2, CO, CO_2, CH_4) \quad (2)$$

Boudouard reaction:

$$C + CO_2 \leftrightarrow 2CO - 162 \text{ kJ/mol} \quad (3)$$

Steam reforming reaction:

$$CH_4 + H_2O(g) \leftrightarrow CO + 3H_2 - 206 \text{ kJ/mol} \quad (4)$$

Water gas reaction:

$$C + H_2O(g) \leftrightarrow CO + H_2 - 131 \text{ kJ/mol} \quad (5)$$

Water–gas shift reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2 + 41 \text{ kJ/mol} \quad (6)$$

Oxidation:

$$C + O_2 \leftrightarrow CO_2 + 408.8 \text{ kJ/mol} \quad (7)$$

Hydrogasification:

$$C + 2H_2 \leftrightarrow CH_4 \ - 75 \text{ kJ/mol} \quad (8)$$

Methane steam reforming reaction:

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O + 206 \text{ kJ/mol} \quad (9)$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O + 165 \text{ kJ/mol} \quad (10)$$

Generation of gaseous fuels from solid materials makes gasification very appealing. Burning of this combustible gas is clean and control is simpler than combustion of solid fuels. Gasification technology development has a long history since the use of coal gas. Attention has also turned towards biomass materials. Various types of biomass have been successfully gasified, including woods, herbaceous plants, energy crops, agricultural residues, and wastes. Utilization of farm processing wastes into energy will increase the value of agricultural output and reduce the operational cost. The technology is relatively economical for use in small scale enterprises and in rural areas. Many types of biomass gasifiers have been developed and demonstrated using agricultural residues as fuels. Among the most popular designs of gasifier adopted was downdraft system, from experimental reactors [18-22] to commercially installed systems [23-26]. Tippayawong *et al*. [23] designed, built and installed a 25 kg/h biomass gasifier system at a local food factory with cashew nut shells used as fuel. At an Indian renewable energy research institute, Bhoi *et al*. [24] designed and developed a 50 kg/h, open core, throatless, downdraft gasifier for loose agricultural residues like groundnut shells, cashew nut shells, shell briquettes, and babul wood. The system was operated at a gas flow rate of 100-130 m^3/h. The intended fuels were shown to be gasified satisfactorily with minor fuel flow problem. A bigger reactor of 100 kg/h was tested and installed to generate steam with producer gas burner in dual fuel mode for a pharmaceutical company [25]. The gasification system utilized sawmill woody waste as feedstock. The gasifier appeared to perform satisfactorily in steam generation application. Economic analysis of the system tested in the field indicated the viability of the gasifier based operation. Pathak *et al*. [26] later introduced a modular design of a 125 kg/h biomass gasifier system, which was subsequently scaled up to 375 kg/h. It was a throat type, downdraft system intended for thermal application. The system was reported to produce good quality of fuel gas consistently and operated without any problem. Patil *et al*. [27] described recent development of a downdraft gasifier with internal cyclonic chamber where turbulent, swirling high temperature combustion took place to convert biomass and crack tars.

These investigations utilized various types of biomass materials. However, to the authors' knowledge, investigation on gasification of spent mushroom substrate has not yet been reported. It is of great interest to apply gasification technology to spent mushroom substrates.

In this work, spent substrates from bag-type mushroom cultivation have been utilized as a source of clean energy via gasification. A simple downdraft fixed bed gasifier system was developed. It was installed and operated at a local mushroom farm, with the aims to reduce operating cost of current sterilization practice by utilizing by-products, and to demonstrate a cost effective and practical producer gas burner to provide process heat with appropriate gasification technology. Experimental data obtained from the operation were presented. Analysis of its energy use and operating cost was conducted, and compared with existing system from conventional practice.

II. Methodology

A. Demonstration Site

The mushroom farm is in Khon Kaen, Thailand. This small enterprise does not only produce mushrooms, it also supplies ready-to-fruit substrate bags to neighboring farms and people. Its hot steam is generated from a water tank heated by a locally made furnace, consuming about 9000 kg of fuelwood a month. This costs around \$300 a month (\$1.00 = 30.45 Thai baht, exchange rate on March 2011). Cost of fuelwood tends to increase as supply is becoming difficult. Furthermore, the farm is situated near residential area where smoke and emissions may be offensive, especially during cold seasons.

Utilization of spent substrates as replacement fuel for wood via gasification was undertaken in this work. Existing wood fired furnace was modified to accommodate a gasifier and a gas burner. Limited test run was carried out to evaluate performance of the system.

B. Spent Mushroom Substrate as Fuel

A substrate for growing mushrooms was mainly made of compacted sawdust, weighing about 1 kg. After 5-6 months used in cultivation, a spent substrate would be about 0.4 kg on average. Its composition was shown in Table 2. Cellulose and hemicellulose accounted for more than 55% of the total mass, with around 20% lignin. Its heating value was about 18 MJ/kg. The shape and size of these substrates can be easily reduced to a uniform block of about 50 mm on each size. Density appeared to be sufficient (above 200 kg/m^3) to be used as a suitable feedstock for gasification.

C. Gasification System

A single-stage, downdraft, throat-type, fixed-bed gasifier was designed and built (shown in Fig. 2). The gasifier components included an insulated cylindrical reactor, a rotatable grate, and an ash pit. Loading of fuel feedstock was done from the top, piling on the grate. The reactor wall was made of firebrick and covered with a steel sheet. Air was induced through circumferential holes by a fan downstream. The gasifier core was designed such that a cross section area was reduced downstream of the air inlets to form a throat or constriction. The reactor volume was designed to require recharging once every two hours when working at rated capacity. The grate area of 0.10 m^2 was designed from specific gasification rate of 250 kg/h/m^2 and the fuel feed rate of 25 kg/h. Ash formed was removed from the gasifier by the rotatable grate and fell into a water sealed, ash pit. The volume of the ash pit was sufficiently large to allow long hour operation without ash removal. The system consists of the gasifier, a gas conditioning system and a gas burner. Fig. 3 shows the gas conditioning system which includes a cyclone, a tube bundle heat exchanger, and an induced draft fan. The system setup at the mushroom farm is illustrated in Fig. 4. Bottom of the main reactor was tightly sealed by water. The gas burner was positioned beneath the existing water tank.

Table 2: Composition of spent substrate (% w/w, dry basis)

	Ref. [9]	Ref. [14]
Cellulose	38.7	40.5
Hemicellulose	18.4	17.0
Lignin	20.2	18.7

D. Test Procedure and Data Analysis

Initially, a small amount of burning charcoal was used to establish a fire on the grate inside the gasification reactor. The induced draft fan was started, drawing air in to sustain combustion. Immediately afterwards, the spent substrates were

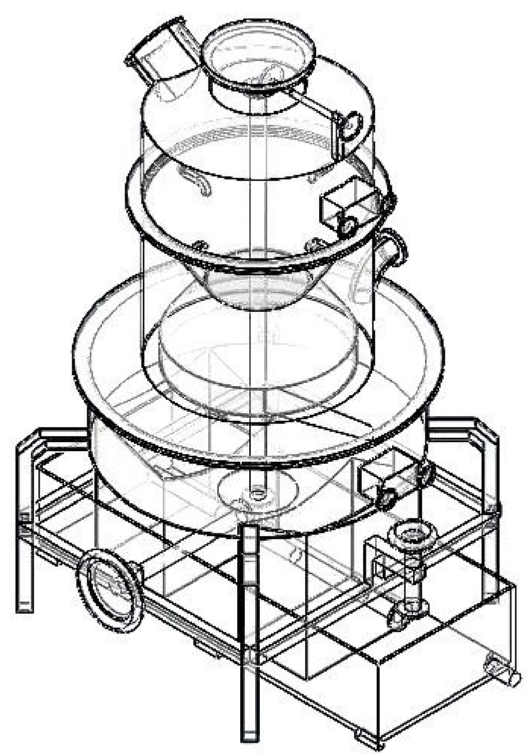

Fig. 2: drawing of the gasifier

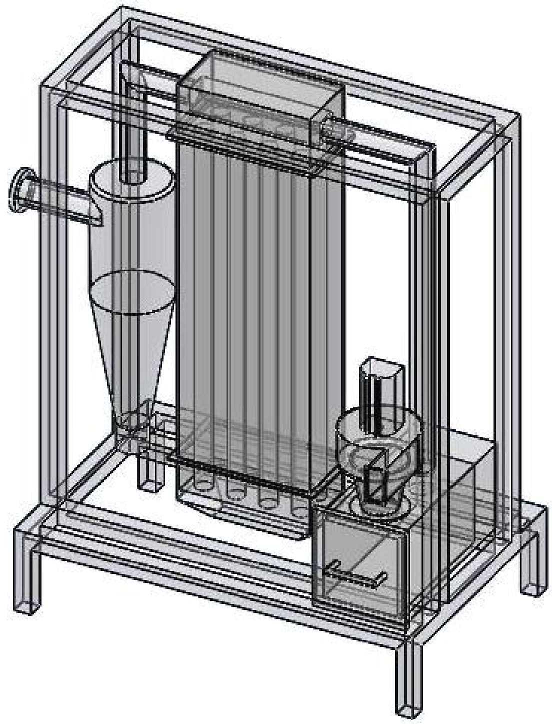

Fig. 3: drawing of the gas conditioning system

loaded and the cover was closed. Air was regulated by valves in such a way that combustible producer gas was generated. This would take about 20-30 min for a stable flame at the gas burner to be established. Producer gas was utilized to provide hot steam to the sterilizing autoclave.

Limited test runs were performed for water boiling test to evaluate the thermal performance of the system [28]. Measurements were taken by monitoring fuel consumption rate and amount of water used on an hourly basis. The gas flow rate was measured with a volume meter. The cool, dry, clean gas was sampled using gas bags and analyzed on a Shimadzu Model GC-8A gas chromatograph for measuring volumetric concentration of H_2, O_2, N_2, CH_4, CO, CO_2. Standard gas mixtures were used for quantitative calibration. Gas temperature at the gasifier exit and flame temperature were measured every 10 minutes with type K thermocouples. Temperatures were recorded continuously on a data acquisition system. The following parameters are calculated;

Specific gasification rate:

$$SGR = \frac{fuel\ mass\ flow\ rate}{reactor\ cross\ section\ area} \tag{11}$$

Gas production rate:

$$GPR = \frac{producer\ gas\ flow\ rate}{reactor\ cross\ section\ area} \tag{12}$$

Fig. 4: configuration of the gasifier system used

Gasification efficiency:

$$\eta_{gas} = \frac{producer\ gas\ energy\ content}{fuel\ energy\ content} \tag{13}$$

Overall thermal efficiency:

$$\eta_{th} = \frac{heat\ to\ steam}{fuel\ energy\ input} \tag{14}$$

III. Results and Discussion

A. System Operation and Performance

Operators with technical experience were trained to run the system by a team of engineers and technicians. The gasifier was able to start within 15 min and attain steady state operation from cold start in about 30-60 min. Fig. 5 shows combustion zone in the gasifier through an observation aperture, after stabilization. The gasification system appeared to operate well and run smoothly without any sign of deterioration or excessive emissions. Producer gas fueled stable flame was established (Fig. 6). No tar problem and no visible smoke were observed. Fuel flow obstruction due to bridging, throat or channel formation did not occur. As a precaution, poking at regular interval was undertaken. The gasification system was also found to generate steam faster than the existing solid fueled furnace.

Several test runs on the system were carried out. Producer gas could be ignited successfully in which bright orange flame was established. Gas production rate was found to be about 480 $m^3/h/m^2$. The gas temperature leaving the reactor was found to vary from 250-350^oC. Composition of the producer gas was shown in Table 3. The gaseous fuel's lower heating value (LHV) was estimated from

Fig. 5: a view of combustion zone in the gasifier

Fig. 6: a view of flame burning producer gas

$$LHV = \sum x_i LHV_i \quad (15)$$

where x_i is volume fraction of producer gas component, and LHV_i is the corresponding heating values of the gas component. At standard temperature and pressure, LHV of different components of the producer gas used in the calculation is CO – 11.57, H_2 – 9.88, CH_4 – 32.79 MJ/m^3 [29].

In this work, it was found to be 3.73 MJ/m^3. This was in the low end of the documented average gas heating value of producer gas from downdraft gasifier systems [30]. This may be attributed to low value of the reactor temperature. Since formation of CO, H_2 and CH_4 is a function of the reactor temperature. Low temperature resulted in low percentage of CO and H_2, hence low value of the heating value of the producer gas. In comparison with those reported in the literature (shown in Table 4), CO and H_2 obtained in this work were indeed comparatively smaller, resulting in relatively lower value of heating value. To increase the energy content of the producer gas, higher flow rate of supply air may be tried. This might consequently increase the reaction temperature, hence higher combustible gas components of producer gas.

Table 3: Composition of producer gas

Component	% v/v
CO	11.55
CO_2	10.27
H_2	9.62
CH_4	3.36
O_2	2.62

Table 4: Comparison of gasifier performance with literature

Reference	feedstock	CO (% v/v)	H_2 (% v/v)	LHV (MJ/m^3)
This work	Spent substrate	12	10	3.7
[18]	Hazelnut shells	21	13	5.0
[19]	Wood chips	24	14	5.3
[20]	Acacia wood	22	12	4.2
[21]	Waste wood	22	12	6.3
[22]	Wood pellets	17-25	10-13	4.1-5.4
[23]	Cashew nut shells	17	5	3.5
[24]	Groundnut shells	-	-	4.4
[24]	Cashew nut shells	-	-	4.5
[26]	Babul wood	-	-	5.0-5.5
[27]	Wood shaving	22	11	6.1
[30]	Pine wood waste	18	30	6.4
[31]	Hard wood	19-23	11-13	3.5-4.0

Nonetheless, for current setup, gasification efficiency was calculated to be 53%. About 10-15% of the feed input remained as solid residues, constituting ash. Visual inspection of ash revealed a small fraction of charcoal left. It was normally disposed of with the water seal. No clinkering or agglomeration was encountered. The thermal energy output was about 18 kW which was sufficient for generating steam to the mushroom bag chamber. Figs. 7 and 8 show energy conversion diagrams of the conventional and new systems. From steam generated and fuel consumption rates, system thermal efficiency was approximated to be around 20%, a significant improvement from the existing steam generator system with only 5% efficiency. Better insulation and better design of steam generator may be implemented to further improve overall thermal efficiency of the new system.

Up to the time of reporting, the system has been in use for over 12 months. Results were consistent throughout the experimental campaign. The operators were satisfied with the installation of the gasifier system in place of existing furnace.

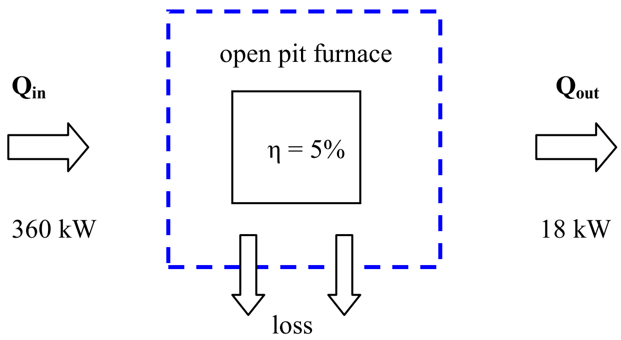

Fig. 7: energy conversion in conventional furnace system

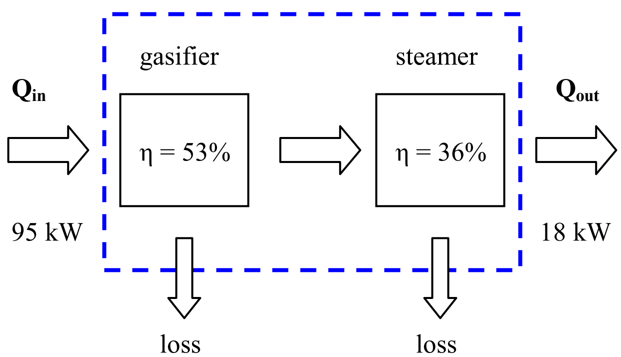

Fig. 8: energy conversion in the gasifier – steamer system

B. *Socio-economic Consideration*

The economic performance was determined as a simple period to positive cash flow. This involves considering the initial investment and additional operating costs, and the wood fuel cost savings. Positive cash flow is reached when the investment and cumulative operating costs equal to the cumulating fuel cost savings. It should be noted that no discount rate is considered here. The overall installation cost included costs for an induced draft fan, gas burner, refractory and structural materials, piping, insulation, painting, engineering design and construction expenses. The additional operating cost was from maintenance cost and miscellaneous operating materials associated with the gasifier system that would not be present in the wood-fired furnace. The gasifier system required an investment of about $3,500 and an additional operating cost of about $10 a month. Since spent substrates were used to replace all of the fuelwood, saving in fuel cost of approximately $300 a month was obtained. This gave rise to a simple period to positive cash flow of less than 12 months. This system was economically attractive to potential users as its useful life is expected to be several years.

Substitution of fuelwood with spent mushroom substrates from mushroom cultivation generated less waste. Combustion of gaseous fuels was much cleaner than burning of solid fuels, hence no more complaints from neighbors are reported. Both gaseous and particulate emissions were expected to reduce significantly. Nonetheless, emission reduction can be further undertaken to the installation, by employing a cost effective control system [32].

Cleaner workplace environment was realized. Effect to human health was reduced. There was also skill development among the farm employees who trained to operate the system. It should be noted an operator does not need to have technical skill. The system is relatively simple to operate. Plan is ongoing to implement similar modification to other farms in the region. This farm can become a demonstration site for mushroom farmers to come and learn from their experience.

IV. Conclusion

Potential use of spent mushroom substrates as replacement fuel for wood was considered in this study. It was found that they were good feedstock for gasification. They have high energy content, similar to fuelwood. The downdraft throat-type gasifier was found to perform satisfactorily with spent substrates in hot steam generation application. Producer gas generated was utilized to fuel a burner at required thermal output rating for sterilization of mushroom growing substrates. Thermal efficiency was significantly improved. No problem during operation was observed. Spent substrates from mushroom cultivation appeared to have potential as a biofuel candidate.

The operators and owner were satisfied with the system. Economic analysis results showed that the gasifier system operation was viable. Simple period to positive cash flow was estimated to be less than a year.

Acknowledgment

The authors would like to thank Mr Asira Bunkham, as well as technical and secretarial staff from the Energy Research and Development Institute, Chiang Mai University. Kind cooperation from Choosak mushroom farm was also appreciated.

References

[1] Mushworld. (March 2011). Oyster Mushroom Cultivation, Available: http://www.fungifun.org/mushworld/Oyster-Mushroom-Cultivation

[2] B. C. Williams, J. T. McMullan and S. McCahey, “An initial assessment of spent mushroom compost as a potential energy feedstock,” *Bioresource Technology*, vol. 79, pp. 227-230, 2001.

[3] K. N. Finney, C. Ryu, V. N. Sharifi and J. Swithenbank, “The reuse of spent mushroom compost and coal tailings for energy recovery: comparison of thermal treatment technologies,” *Bioresource Technology*, vol. 100, pp. 310-315, 2009.

[4] K. N. Finney, V. N. Sharifi and J. Swithenbank, “Combustion of spent mushroom compost and coal tailing pellets in a fluidized bed,” *Renewable Energy*, vol. 34, pp. 860-868, 2009.

[5] A. V. Bridgwater, “Renewable fuels and chemicals by thermal processing,” *Chemical Engineering Journal*, vol. 91, pp. 87-102, 2003.

[6] M. Lisy, M. Balas, J. Moskalik and J. Pospisil, “Atmospheric fluidized bed biomass and waste gasification,” *WSEAS Transactions on Power Systems*, vol. 4, pp. 157-166, 2009.

[7] I. Ionel, F. Popescu and L. I. Dungan, "Bioenergy for district heating and cooling systems," *International Journal of Energy*, vol. 5, pp. 1-8, 2011.
[8] G. Trif-Tordai, I. Ionel and F. Popescu, "Novel RES based co-combustion technology," *WSEAS Transactions on Environment and Development*, vol. 6, pp. 561-570, 2010.
[9] J. J. Qiao, Y. F. Zhang, L. F. Sun, W. W. Liu, H. J. Zhu and Z. Zhang, "Production of spent mushroom substrate hydrolysates useful for cultivation of Lactococcus lactis by dilute sulfuric acid, cellulose and xylanase treatment," *Bioresource Technology,* vol. 102, pp. 8046-8051, 2011.
[10] E. Medina, C. Paredes, M. D. Perez-Murcia, M. A. Bustamante and R. Moral, "Spent mushroom substrates as component of growing media for germination and growth of horticultural plants," *Bioresource Technology*, vol. 100, pp. 4227-4232, 2009.
[11] E. Herrero-Hernandez, M. S. Andrades, M. S. Rodriguez-Cruz and M. J. Sanchez-Martin, "Effect of spent musgroom substrate applied to vineyard soil on the behaviour of copper-based fungicide residues," *Journal of Environmental Management*, vol. 92, pp. 1849-1857, 2011.
[12] K. L. Lau, Y. Y. Tsang and S. W. Chiu, "Use of spent mushroom compost to bioremediate PAH-contaminated samples," *Chemosphere*, vol. 52, pp. 1539-1546, 2003.
[13] C. K. Zhang, F. Gong and D. S. Li, "A note on the utilization of spent mushroom composts in animal feeds," *Bioresource Technology*, vol. 52, pp. 89-91, 1995.
[14] W. S. Kwak, S. H. Jung and Y. I. Kim, "Broiler litter supplementation improves storage and feed-nutritional vale of saw dust-based spent mushroom substrate," *Bioresource Technology,* vol. 99, pp. 2947-2955, 2008.
[15] S. Chopra and A. Jain, "A review of fixed bed gasification systems for biomass," *Agricultural Engineering International: CIGR E-journal*, vol. 9, 2007. Available: http://www.cigrjournal.org
[16] V. Kirubakaran, V. Sivaramakrishnan, R. Nalini, T. Sekar, M. Premalatha and P. Subramanian, "A review on gasification of biomass," *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 179-186, 2009.
[17] I. De Bari, D. Barisano, M. Cardinale, D. Matera, F. Nanna and D. Viggiano, "Air gasification of biomass in a downdraft fixed bed: a comparative study of the inorganic and organic products distribution," *Energy and Fuels*, vol. 14, pp. 889-898, 2000.
[18] M. Dogru,C. R. Howarth, G. Akay, B. Keskinler and B. Malik, "Gasification of hazelnut shells in a downdraft gasifier," *Energy*, vol. 27, pp. 415-427, 2002.
[19] Z. A. Zainal, A. Rifau, G. A. Quadir and K. N. Seetharamu, "Experimental investigation of a downdraft biomass gasifier," *Biomass and Bioenergy*, vol. 23, pp. 283-289, 2002.
[20] A. K. Sharma, "Experimental study on 75 kW_{th} downdraft (biomass) gasifier system," *Renewable Energy*, vol. 34, pp. 1726-1733, 2009.
[21] P. N. Sheth and B. V. Babu, "Experimental studies on producer gas generation from wood waste in a downdraft biomass gasifier," *Bioresource Technology,* vol. 100, pp. 3127-3133, 2009.
[22] C. Erlich and T. H. Fransson, "Downdraft gasification of pellets made of wood, palm-oil residues respective baggase: experimental study," *Applied Energy*, vol. 88, pp. 899-908, 2011.
[23] N. Tippayawong, C. Chaichana, A. Promwungkwa and P. Rerkkriangkrai, "Gasification of cashew nut shells for thermal application in local food processing factory," *Energy for Sustainable Development*, vol. 15, pp. 69-72, 2011.
[24] P. R. Bhoi, R. N. Singh, A. M. Sharma and S. R. Patel, "Performance evaluation of open core gasifier on multi-fuels," *Biomass and Bioenergy*, vol. 30, pp. 575-579, 2006.
[25] S. R. Patel, P. R. Bhoi and A. M. Sharma, "Field testing of SPRERI's open core gasifier for thermal application," *Biomass and Bioenergy*, vol. 30, pp. 580-583, 2006.
[26] B. S. Pathak, S. R. Patel, A. G. Bhave, P. R. Bhoi, A. M. Sharma and N. P. Shah, "Performance evaluation of an agricultural residue-based modular throat-type down-draft gasifier for thermal application," *Biomass and Bioenergy*, vol. 32, pp. 72-77, 2008.
[27] K. Patil, P. Bhoi, R. Huhnke and D. Bellmer, "Biomass downdraft gasifier with internal cyclic combustion chamber: design, construction and experimental results," *Bioresource Technology,* vol. 102, pp. 6286-6290, 2011.
[28] N. L. Panwar and N. S. Rathore, "Design and performance evaluation of a 5 kW producer gas stove," *Biomass and Bioenergy*, vol. 32, pp. 1345-1352, 2008.
[29] A. Jain, "Design parameters for a rice husk throatless gasifier," *Agricultural Engineering International: CIGR E-journal*, vol. 8, 2006. Available: http://www.cigrjournal.org
[30] N. S. Mamphweli and E. L. Meyer, "Implementation of the biomass gasification project for community empowerment at Melani village, Eastern Cape, South Africa," *Renewable Energy*, vol. 34, pp. 2923-2927, 2009.
[31] A. K. Sharma, "Modeling and simulation of a downdraft biomass gasifier I: model development and validation," *Energy Conversion and Management*, vol. 52, pp. 1386-1396, 2011.
[32] J. Hrdlicka and B. Sulc, "Advanced features of a small-scale biomass boiler control for emission reduction," *International Journal of Energy*, vol. 5, pp. 62-69, 2011.

Nakorn Tippayawong received his B.Eng. and Ph.D. degrees in Mechanical Engineering from Imperial College, UK in 1996 and 2000, respectively. He is currently an Associate Professor at the Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Thailand. His research interests include biomass utilization, energy efficiency improvement, and emission control. So far, he has published more than 50 papers in peer reviewed international journals.

Chutchawan Chaichana received his B.Eng. in Mechanical Engineering from Chiang Mai University, Thailand in 1994, M.Eng. and Ph.D. degrees from University of Melbourne, Australia in 1999 and 2003, respectively. He is currently an Assistant Professor at the Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Thailand. His research interests include renewable energy, heat recovery, and thermal engineering.

Anucha Promwungkwa received his B.Eng. in Mechanical Engineering from Chiang Mai University, Thailand in 1989, and M.Eng. in Energy Technology from Asian Institute of Technology, Thailand in 1995 and Ph.D. degrees from Virginia Polytechnic Institute and State University, USA in 1999. He is currently an Assistant Professor at the Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Thailand. His research interests include energy conservation, heat recovery, and material engineering.

Prasert Rerkkriangkrai received his B.Eng. in Mechanical Engineering from Chiang Mai University, Thailand in 1986, and M.Eng. in Energy Technology from Asian Institute of Technology, Thailand in 1988, respectively. He is currently an Associate Professor at the Department of Mechanical Engineering, Faculty of Engineering. He is also the Director of Energy Research and Development Institute Nakornping, Chiang Mai University, Thailand.