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Measurements of fuel burn rate, emissions and thermal efficiency from a domestic two-stage wood-fired hydronic heater

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ABSTRACT

An experimental study is conducted of a two-stage wood-fired hydronic heater (WFHH). The WFHH contains two combustion chambers. The first is associated primarily with wood pyrolysis while the second, located down stream, is designed for secondary burning of undesirable emissions. A piezoelectric load cell based apparatus is developed to obtain direct measurements of fuel burn rate (FBR) - avoiding possible inaccuracies of standardized (full appliance weighing) approaches used for certification. To check the internal consistency of the experimental measurement, a theoretical mass loss relation is developed and used for reducing data and to explain the physical mechanism responsible for the existence of the experimentally observed global maximum burn rate. A system level numerical model is also developed based on a combination of well-stirred reactor theory and chemical equilibrium to provide estimates of flue exhaust products and temperature. Overall agreement between experiments and model predictions are reasonable for temperature and major combustion species. Experimental emissions maps within a temperature/equivalence ratio state space are used to demonstrate the current operating path for this WFHH. Average thermal efficiencies are measured in the range of 48–55%. These measurements are found to be internally self-consistent and provide guidance for more complete theoretical studies.

1. Introduction

The World Health Organization estimates that over three billion people rely on wood and other traditional solid fuels for cooking and heating [1]. In particular, from the roughly 100 EJ/a of sustainable global biomass energy potential available today, 40 EJ/a is used for energy and 60% of that is used only in Asia where demand far exceeds supply [2–6]. With diminishing fossil fuel resources, biomass is expected to account for up to 30% of the worlds annual demand for energy by 2050 [2]. The growing demand for hydronic heaters and other wood burning appliances has sparked an effort to provide stricter guidelines on the certification of these systems. The United States Environmental Protection Agency (EPA) has recently defined new regulations for wood burning appliances including wood stoves, masonry heaters, pellet-burning stoves and hydronic heaters [7]. Newer wood fired systems are often equipped with a water jacket hydronic system to improve heat transfer efficiencies and to be compatible with existing hot-water heating systems.

A recent review on the use of biomass for boilers was done by Saidur et al. [8] and may be grouped into pellet [9,10], wood chips [11,12], cord-wood, wood briquettes [13], and coal [14] based systems. For pellet and wood chip feed systems, the fuel flow rate is controlled, allowing for quasi-steady-state operation. Consequently, efficiencies and emissions are better understood and controlled. Less is known about cord-wood systems since they are run as a completely unsteady batch process.

The purpose of this study is to experimentally explore the performance of a two-stage, downdraft, hydronic heater system and to confirm the results by developing a system level model to estimate thermal and combustion performance as a first approximation. This permits a general check on the internal consistency of the measurements as well as providing general guidance for future endeavors.

2. Experiments

2.1. Hydronic heater setup and operation

A test facility is developed for this WFHH, similar in basic

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Nomenclature

bb	BIOBLOCK®
h	heat transfer coefficient [W/m^2−K]
h_i	enthalpy [MJ/kg]
Δh	heat [MJ/kg]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
t	time [hr]
A	area [m^2]
C	heat capacity [J/kg−K]
G	Gibbs free energy [kJ/kg]
H	enthalpy [kJ/kg]
L	latent heat [MJ/kg]
M	normalized Mass
Q	heat [J]
$\dot{Q}$	heat rate [W]
S	entropy [kJ/K]
T	temperature [K]
Y	species mass fraction
Z	mixture fraction

Greek

α	sensitivity number
ρ	density [kg/m^3]
τ	normalized time
ϕ	equivalence ratio
σ	Stefan-Boltzmann constant [W/m^2−K^4]
Δ	$\Delta F = \int \dot{F} dt$

subscripts/superscripts

air	air
b	boiler
c	constant
$comb$	combustion
del	delivered
f	fuel
fg	fuel to gas
$flue$	flue
g	gas
gb	gas to boiler
i	i^{th} species
in	in
n	n^{th} term
o	initial
out	out
p	pyrolysis
$peak$	peak, where $-\dot{m}_f$ is maximum
s	steel
$stor$	storage
th	thermal
w	water

approach to that of Kang et al. [15]. Fig. 1 shows (a) the front and (b) a cut-away of the Econoburn (Brocton, NY) EBW-200 WFHH used in this study. The testing facility (Fig. 1c) consists of the WFHH, primary and secondary water circulation loops, and heat exchanger. Early during a run, pump P1 is on and P2 is off to circulate the hot water through the boiler until reaching 150° F (339 K). After the water comes to temperature, the second load loop (P2) is activated and P1 is turned off. The load loop contains a 300,000 BTU/hr (87.9 kW) counterflow heat exchanger to transfer heat from the boiler to a cold thermal sink. The heat rate is monitored by recording the water temperatures and flow rates, providing a detailed trend of the supplied heat load.

2.2. *Fuel burn rate measurement and fuel type*

Performance characterization of a WFHH requires accurate monitoring of the instantaneous fuel burn rate (FBR), inlet and outlet temperatures of any working fluid, and emissions measurements from the exhaust. A common approach for solid fuel mass measurements is to instantaneously measure the total weight of the boiler with fuel burning in the combustion chamber and use the total weight change to infer the time rate of change of the mass of the fuel. Since the initial fuel load often weighs less than 5% of the total system, resolution questions arise regarding the accuracy. This issue is further compounded when uncertainties of loads from plumbing, electrical and exhaust flue connections, *etc.* are considered. This not only makes it difficult to detect minute mass changes, but also even small force loading fluctuations in the boiler could significantly affect the inferred burn rate. To mitigate these uncertainties, a unique real time fuel burn rate monitor (RTFBRM) is designed to directly measure mass loss in the primary chamber as a function of time. Fig. 2a shows the RTFBRM assembly consisting of a basket suspended by two rods. The rods run through the top of the boiler into the combustion chamber. The upper cross member rests on a piezoelectric based compression load cell shown in Fig. 2b. The pancake load cell (Stellar Technology) is thermally insulated to avoid any biases induced from thermal gradients. The fittings are packed with high-temperature carbon laced rope to minimize contact friction.

To minimize run-to-run variation, BIOBLOCKS® (Summit Wood Industries), are used. The blocks are made from 100% hardwood chips (primarily red oak). The moisture content (8.3% dry-basis by mass) and density (1.15 g/cm^3) of the blocks were measured in accordance with ISO standard 3130. A full load run requires 32 blocks ($\simeq$62 lbs, 28 kg) to conform to current testing standards. Fig. 2c shows the loading sequence of the BIOBLOCKS® fuel. Ignition of the fire is made in four locations (each side of the packed fuel load) using a propane torch. Consistent run terminations are achieved when flue exhaust: temperatures fall below 200° F (366 K), O_2 content is greater than 19% and CO is less than 1000 ppm.

2.3. *Emission measurements*

During the boiler run, exhaust flue emissions measurements are recorded using a Testo 330-2 LL gas analysis meter. The analyzer takes measurements of the O_2, CO, NO, pressure and temperature from the center of the exhaust stream.

The CO_2 recorded by the Testo analyzer is estimated from the O_2 measurement and limited by the maximum theoretical value of CO_2 based on the fuel composition at the stoichiometric limit. It is therefore subject to interpretation and inaccurate for some conditions. To avoid this problem, a method is developed to determine the flue gas composition given the direct measurements of CO, NO and O_2. In this approach, the wood fuel is assumed to have the general composition $C_xH_yO_wN_z$ and burn according to the overall reaction: $C_xH_yO_wN_z + a\,(O_2 + 3.76N_2) + b\,H_2O \rightarrow c\,CO_2 + d\,H_2O + e\,H_2 + f\,CO + g\,NO + h\,O_2 + i\,N_2$, where x, y, w and z are assumed to be 1.0, 1.7, 0.72 and 0.001, respectively which is representative of