SIMULATION OF A COMBINED SPACE AND WATER HEATING SYSTEM FIRING PELLET FUEL FOR COMMERCIAL/RESIDENTIAL APPLICATION

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ABSTRACT
This paper describes the development of a real-time dynamic simulator that is configurable to simulate a variety of commercial / residential combined space heating and domestic hot water systems.   The simulation allows the designer the ability to test different physical configurations under various operating conditions and to optimize a system design for specific operating requirements.   The simulator was built using the G2 expert system shell which is a product of the Gensym Corporation.

INTRODUCTION
Efficiency gains, improved system performance, and low consumer cost are all recognizable benefits associated with the development of oil and gas integrated residential energy systems. With natural gas, high efficiency integrated space and hot water heating systems can have seasonal efficiencies over 90%, with overall fuel savings and pollutant reductions of 35-45%, when compared to conventional non integrated systems. Properly integrating oil-fired space and tap water heating systems can raise overall efficiencies by 10-30%, with a commensurate reduction in NO_x and CO_2 emissions, with an even greater reduction of incomplete combustion products.

Biomass fuel technology advancements, particularly in the area of pellet fuel, are now revolutionizing how biomass is likely to be used in our homes for generation to come. Pellet fuel overcomes many of the major impediments that seriously limit the attractiveness of biomass as fuel. The pellet industry turns a biomass residue destined for non-productive landfill into a valuable energy commodity that is very competitive as a fuel. Unlike traditional wood use which varies widely in fuel quality, pellet fuel is high grade, conforming to industrial standards that define ash content (less than 1%), moisture content (less than 5%) and dry calorific value of 19,773 kJ/kg (8,500 Btu/lb). Biomass pellets are much easier to handle, transport, and store compared to conventional core wood. Biomass pellet fueled stoves are very energy efficient, clean burning and offer the customer automation and convenience.

CANMET Energy Technology Centre is focused on developing advanced residential integrated systems using biomass pellets as a fuel. Combining two or more end uses, such as space and tap water heating, with one energy generator into an integrated system has the potential to be an effective means to substantially increase efficiency and to reduce emissions from residential biomass combustion appliances, at reduced overall capital costs. However, the design of an integration energy system poses many equipment and systems challenges along with a host of operational variables that have to be optimized.   Considerations include: furnace sizing, burner modulation requirements, furnace startup and shut down scenarios, hydronic systems configurations, tap water segregation, optimal thermal fluid temperature, heat storage, load following and optimization, and systems's reliability. This set of complex design considerations and trade-off can best be effectively optimized using appropriately designed simulation software.

The simulator was originally developed to design and test various combined space and water heating system designs firing pelletized wood fuel.   It not only tests the design but can be used to develop and test control strategies and operating practices. Although the simulator was originally used for pellet fire systems, the technology applies equally to the more conventional gas and oil fired systems.

This paper will present the configuration of the pellet fired system, the theory used for the major components in the system and then the architecture and design of the simulator.   It will comment briefly on how the simulator was used in the design process.

THE PELLET-FIRED SPACE AND WATER HEATING SYSTEM

High-efficiency pellet-fired integrated home energy systems (Figure 1) comprised components that can be configured in a number of ways to suit site specific installation needs. Major system components include, a fuel storage and supply system, a pellet burner, fuel and ash removal system, a furnace air supply and exhaust module, boiler, hot water storage tank, a forced air fan coil unit and a plate to plate domestic hot water heat exchanger (Figure 2).

The fuel storage management and handling system allows a typical home owner to receive and store 800 kg. of fuel, sufficient fuel to cover a homeowner's space and hot water energy requirements for a month during Canadian winter conditions. Fuel from the storage bin is monitored and augered to the furnace fuel supply hopper.

The specific control strategy is designed to achieve the desired set points to ensure safe operation, maximum energy efficiency, reduced furnace cycling, comfort, optimum fan speeds to optimize comfort and to minimize noise levels. Features of the control strategy include intelligent defaults and occupant controlled set points for space and hot water heating, air coil settings, furnace monitoring for proper combustion startup and shutdown, proof of fluid flows and temperature monitoring, furnace startup and shut down and modulating fuel firing rates .

The furnace incorporates a variable speed induced draft fan to minimize excess air requirements, optimize combustion performance and load following with a step down ratio of 3 to 1. Overall operating efficiencies are in the range of 80 %. The control strategy also focuses on minimizing furnace cycling.

The combustion burner is encased in a waterwall boiler, the burner is air cooled by its own air supply, and the ash dump is appropriately lined and insulated to meet all standards and code requirements. The furnace exhaust will be fitted with a high temperature cut-off switch.

Space Heating
Space heating capacity of the system as proposed would be 14 kW (77,000 Btu/hr). Three furnace firing rates are controlled to follow the heating load in a fashion that maximizes energy efficiency. The water supply temperature to a forced air fan coil unit is controlled between 60 and 71 deg C.(140 to 160 deg F).

The space heating control can be set to ensure that under all conditions the space heating supply air temperature of 47C (117F) is maintained. At design conditions, our air handler will have a supply air temperature of 51C (123F).

Domestic Hot Water
The smart control that prioritize domestic hot water over space heating means the actual water available for domestic use is much greater than current guidelines. The recovery rate is 300 litres/h (80 usgph) (based on 50C/90F temperature rise). The first hour rate is 416 litres (110 usg).

The burner input of 34 kW (maximum120,000 Btu/hr) with an output of 28kW (96,000 Btu/hr) is capable of meeting the 14kW (77,000 Btu/hr) space heating load with a 20% reserve for domestic hot water. The smart controls that prioritize domestic water over space heating means the actual water available for domestic use will be much greater than measured using the current guideline rating method. The delivery temperature is monitored to ensure it will not exceed 60C (140F) using a mixing valve and bypass configuration.

The hot water tank will be fitted with electrical resistance heating to provide backup for domestic hot water and space heating needs.

THEORY
For the simulator to behave as required, certain components must have transient behaviour. Transient behaviour is required for the space and the tank, due to their ability to store heat. All other components in the system have minimal thermal capacitance (the ability to store heat) and therefore were treated as behaving in steady state. This steady state assumption is used for the air coil, domestic hot water heat exchanger, boiler and piping. It could be argued that the boiler should have a transient behaviour, however, it was treated as instantaneously coming to thermal equilibrium. This assumption may be improved in the future.

The theory that will be presented in this section will be for the major components including the treatment of the heated space and the storage tank.

The other components in the system were modeled using simple heat and mass balances. The domestic hot water heat exchanger was modeled using the NTU method.

Modeling of the Heated Space

The heated space can be treated as an enclosure that transfers heat to the outside environment through a single equivalent wall. This is a simplification of the heated space, however, the purpose of this project was to concentrate on the behaviour of the heating system. This gives the appropriate overall behaviour of the heated space because it replicates the overall conductance to the temperature sink and the overall thermal capacitance of the space.

The heat transfer of the wall of an enclosed space can be expressed as:

$$Q = \frac{A \times (T_o - T_i)}{(1/h_o + \Delta x / k + 1/h_i)} \qquad \ldots(1)$$

Where:

Q	Heat transfer (kW)
A	Equivalent heating surface of the house (m^2)
To	Outside temperature (deg C)
Ti	Inside temperature (deg C)
ho	Equivalent outside film coefficient (kW/m^2.deg C)
hi	Equivalent outside film coefficient (kW/m^2.deg C)
? x	Equivalent thickness of the wall (m)
k	Equivalent conductivity of the wall (kW/m.deg C)

An overall equivalent heat transfer coefficient (U) can be solved for the enclosure

$$U = \frac{1}{1/h_o + \Delta x / k + 1/h_i} \qquad \ldots(2)$$

Therefore, the expression in equation (1) can be simplified to:

$$Q = U \times A \times (T_o - T_i) \qquad \ldots(3)$$

For the sake of this analysis the product U x A can be written as a single conductance (G) which can be called the heat loss factor .

This reduces the equation to

$$Q = G \times (T_o - T_i) \qquad \ldots(4)$$

Determination of Heat Loss Factor (G)

The heat loss factor factor describes how quickly heat is being lost on average from a space. This heat output would be required to be supplied by the heating system.

The average temperature differential is :

$$\gamma = Degree - days / heating\_period \qquad \ldots(5)$$

Therefore the average outside temperature is :

Average Outside Temperature
= The Reference Temperature - ?   ...(6)

Using as an example Ottawa, Ontario, Canada as a design condition we know the following:

Design Temperature	-25 deg C
Degree Days	4763 deg C- Days
Reference room temp	18 deg C
?	23 deg C
Average Outside Temp	-5 deg C
Annual fuel consumption	75 GJ/yr (14880 KJ/hr based on 210 heating days/yr)
Heat loss factor (G)	647000 kJ/deg C . hr

Although infiltration can be a factor, this heat loss is included in the heat loss factor using this analysis method.

Heat Capacitance Factor (C)

Space heating requires transient modeling because dwellings of different sizes, construction and materials will store various amounts of heat. Heat lost from the space will cause an overall drop in temperature of the space depending upon the equivalent thermal capacitance of the space.

$$G \times (T_o - T_i) = \frac{C \times (T'_i - T_i)}{d\theta} + Q_{delivered} \qquad \ldots(7)$$

d?	Time period (s)
T'i	New temperature after d? (deg C)
Q delivered	Heat supplied by the heating system (kW)

If $Q_{delivered} = 0$ (the heating system is not running)

then this equation can be used to determine heat capacitance factor (C) of the space:

$$C = \frac{G \times d\theta \times (T_o - T_i)}{(T'_i - T_i)} \quad …(8)$$

This equation can be solved experimentally using a cool down test. At the required temperature differential (?) and no heat delivered from the heating system, the rate of temperature drop (ß) of the enclosure needs to be recorded.

$$\beta = \frac{(T'_i - T_i)}{d\theta} \quad …(9)$$

Therefore

$$C = \frac{G \times \gamma}{\beta} \quad …(10)$$

Modeling of the Storage Tank
The change in heat over a time period within the storage tank is equal to the difference between the heat input and the heat output and losses during that period. A generalized heat balance for the tank can be written as follows:

$$\Delta Q_{tank} = Q_{input} - Q_{output} - Q_{losses} \quad …(11)$$

Heat Input (Q$_{input}$)

$$Q_{input} = \dot{m}_{boiler\_water} \times Cp \times (T_{boiler} - T_{tank}) \quad …(12)$$

Where:

$$Q_{input} = (\eta / 100) \times Q_{fired} \quad …(13)$$

Where:

m_{boiler_water}	Mass flow of the boiler water(kg/hr)
Ttank	Temperature of water in tank (deg C)
Tboiler	Temperature of water out of boiler (deg C)
Cp	Specific heat of water (kJ/kg.deg C)
?	Efficiency of boiler (%)
Q$_{fired}$	Heat input from fuel firing (kJ/hr)

Heat Storage Differential
The difference in heat of the tank will cause the temperature of the tank to vary in accordance with:

$$\Delta Q_{tank} = \frac{m_{tank} \times Cp \times (T'_{tank} - T_{tank})}{d\theta} \quad …(14)$$

Heat Output
The heat leaving the tank is the sum of the heats to the heat exchanger and the air coil:

$$Q_{out} = Q_{heat\_exchanger} + Q_{air\_coil} \quad …(15)$$

Where:

Q$_{heat\_exchanger}$	Heat duty of the heat exchanger
Q$_{air\_coil}$	Heat duty of the air coil

Solving equation (14) for the next temperature of the tank:

$$T'_{tank} = \frac{d\theta}{m_{tank} \times Cp} \Delta Q_{tank} + T_{tank} \quad …(16)$$

SIMULATOR DESIGN
The simulator was built using an expert system shell called G2 developed by the Gensym Corporation. The shell uses an object oriented data structure and therefore, objects can be created having specific functions and attributes.

Data Objects
The objects used in this simulation are :

TANK	a tank
HEX	the domestic hot water heat excanger and mixing valve assembly
SHOWER	a domestic hot water draw that could represent a shower, sink, washer etc by user configuration
SPACE	this is the heated space that can be configured for different geographical locations and various types of use and construction
COIL	the air coil used to heat the forced air system
BOILER	a hot water boiler

Each object is configurable by the user. There are three types of attributes (data) associated with each object.

S	Real time user modifiable input
S	Configuration input (must be set before the simulation starts and will be constant for the simulation)
S	Output (values which) are calculated by the simulation and these values are simply

displayed to the user

Real Time User Input
The user can control the following time-variant boundary conditions in real time throughout the simulation:

For the space:
S   room thermostat set-point temperature (deg C)
S   outside ambient temperature (deg C)

For the domestic water:
S   set-point temperature for hot water (deg C)
S   service water supply temperature (deg C)

For the tank:
S   boiler cut-out temperature (deg C)
S   boiler cut-in temperature (deg C)

The user can also turn on and off any number of configurable domestic hot water demands.

Configuration Input
These include the size of the tank, flowrates of the domestic hot water demands, physical attributes of the components etc.   These inputs have been configured to be established at the beginning of the simulation and not configurable in real time.

Rules
There are two types of rules that govern the operation of the simulator, "initially" rules and "whenever" rules.

"Initially" rules are run at the beginning of the simulation. In this simulation these rules are used to initialize data and to start continual procedures. In this case there is one rule to set the conditions of the tank at startup and another to start a continuous procedure called "space_proc". The 'space_proc' starts the calculation of the heat loss of the space which is a continual process during the heating season.
"Whenever" rules are triggered by events such as reaching cut-in temperatures.

Procedures
Procedures are usually triggered by a rule and are used to perform a computational task. There are two types of procedures used in this simulation. There are those that perform a heat balance and mass

balances on specific system components, and those used to start, stop and initialize values for components .

The procedures that perform the heat and mass balances are:

TANK_PROC
SPACE_PROC
SHOWER_NUMBER_PROC

A brief descrciption of these procedures is as follows:

TANK_PROC
This procedure is used to perform a heat balance on the tank and calculate all temperatures associated with the tank and water entering and exiting the tank. This heat balance is a transient balance that takes into consideration the heat storage ability of the tank. This balance is run throughout the simulation and as components such as the air coil, boiler and domestic hot water heat exchanger are turned on and off and numerical values such as the tank cut-in and cut-out temperature are modified by the user.

SPACE_PROC
This procedure performs the heat balance on the space based upon the physical and environmental attributes of that space. This, once again, is a transient analysis based on the theory presented.

SHOWER_NUMBER_PROC
This procedure, upon noticing that there is domestic hot water being drawn from the system, will do a complete heat balance on the domestic hot water heat exchanger using the NTU method. It will also resolve the heat balance and mass balance associated with the mixing valve.

There are also a number of less consequential procedures that perform the tasks of turning components on and off and set appropriate flows and temperatures when these components are operating.

Logic Flow
The main logic flow is as follows:

1.   Start the simulation
2.   Initialize the tank data
3.   Calculate the heat balance on all system components that are operating
4.   Start at time = 0
5.   Wait for a time step

6. Calculate new temperatures within the system including the space and perform a heat balance on all components that are operating
7. Repeat steps 5 and 6 until simulator is shutdown

The space loses heat continually with various realtime changes in the thermostat setpoint and the outside temperature condition. Once the room temperature decreases to below the lower deadband on the thermostat, the air coil will turn on and heat will be drawn from the tank to heat the space.

Heat is also removed from the tank as domestic hot water is drawn from the system by a variety of user controlled demand systems such as showers. Once the temperature of the tank decreases below the cut-in temperature the boiler will automatically turn on and deliver heat to the tank.

Graphical User Interface
The graphical user interface (Figure 3) shows a variety of configurable graphics. To change the attributes of the tank for example the user selects the tank which causes a table to appear. The user then enters a different value in the table. Data sliders that are used to change many of the real time inputs for the components. Values can be graphed at the bottom to monitor the simulation as it proceeds. Water demands can be configured and turned on and off using the action buttons to the side of water draw object (noted as shower1, shower2, etc.).

USE OF THE SIMULATOR
The simulator was used to design the heating system shown in figure 1 and to configure the control system. This use can be summarized as follows:

S   size the tank, boiler, air coil and heat exchanger
S   establishing firing rates for the boiler and under which conditions to use these firing rates
S   determine the best cut-in and cut-out tank temperatures for starting and stopping the boiler
S   establishing an acceptable deadband on the thermostat
S   determining how the heating system will perform on different houses for various ambient temperature and hot water use scenarios

DISCUSSION AND CONCLUSIONS
The simulator was used to develop a preliminary design for the pellet fired combined space and domestic hot water and to give us an idea of how to control the system. Many different design and control scenarios were tested before developing an optimal arrangement for a specific set of constraints.

The specific design features for this installation that that were derived from the simulations were

S   boiler firing rates and flowrates
S   optimum storage tank capacity
S   domestic hot water heat exchanger size, flowrates
S   mixing valve parameters
S   fan coil size, flowrates and temperatures
S   control set-points such as cut-in and cut-out temperatures and thermostat dead bands

In the next phase of this project the actual performance of the system will be tested and compared against the simulator runs.

The major conclusions from this work were
1. It has been shown that an appropriately designed simulation software can effectively be used to analyze complex design considerations and optimize the design of a system of this nature.
2. Use of a simulator is an extremely valuable tool in developing and testing control strategies.
3. In the future there would be some value in developing a transient behaviour for the boiler component.

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4. Hayden, A.C.S., Braaten, R., 'Efficient Residential Oil Heating', NRCan report # SP 88-1, Cat. No. M38-15/88-1, 1988.

Figure 1   Schematic Integrated Space and Water Heating Furnace
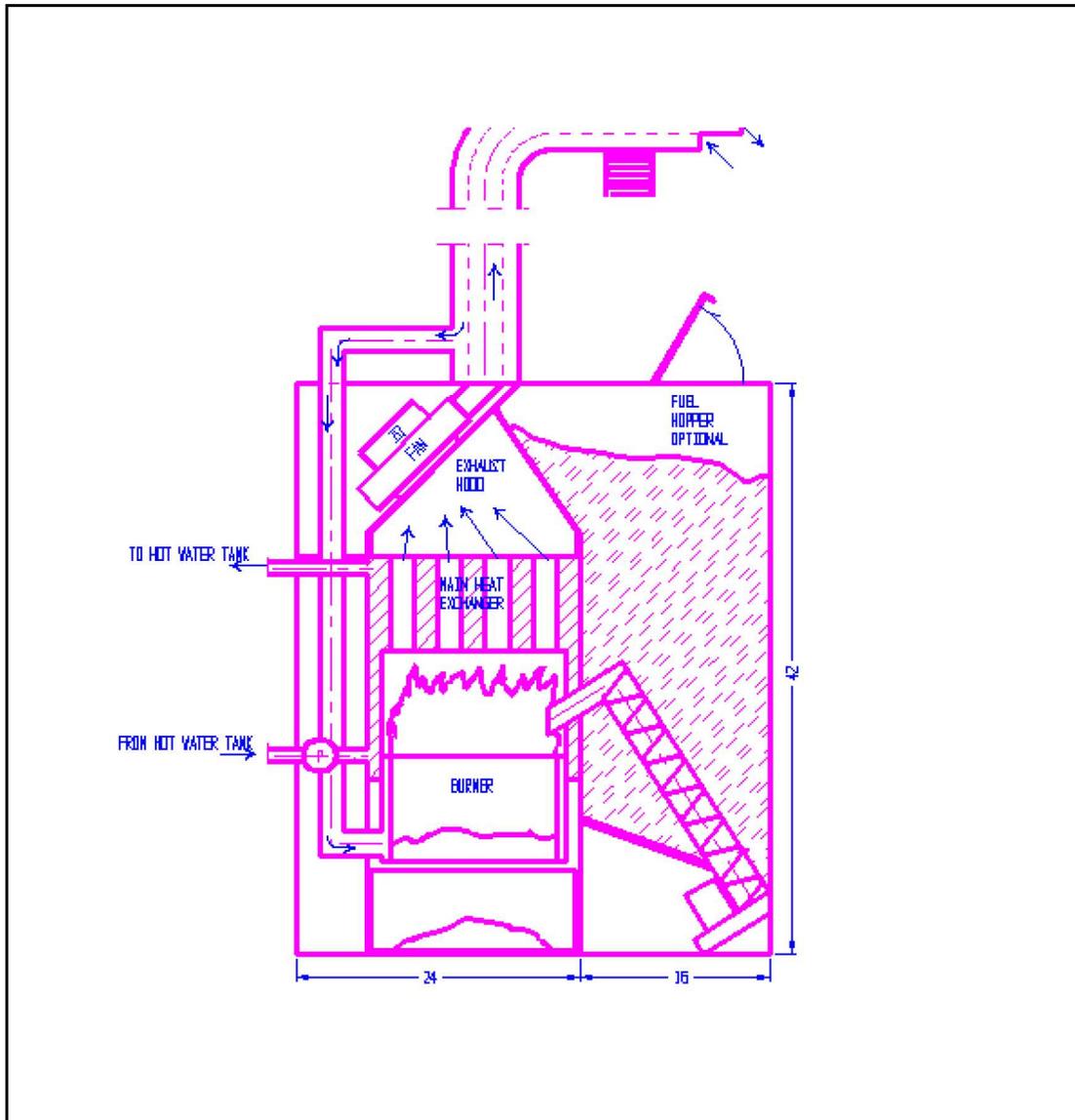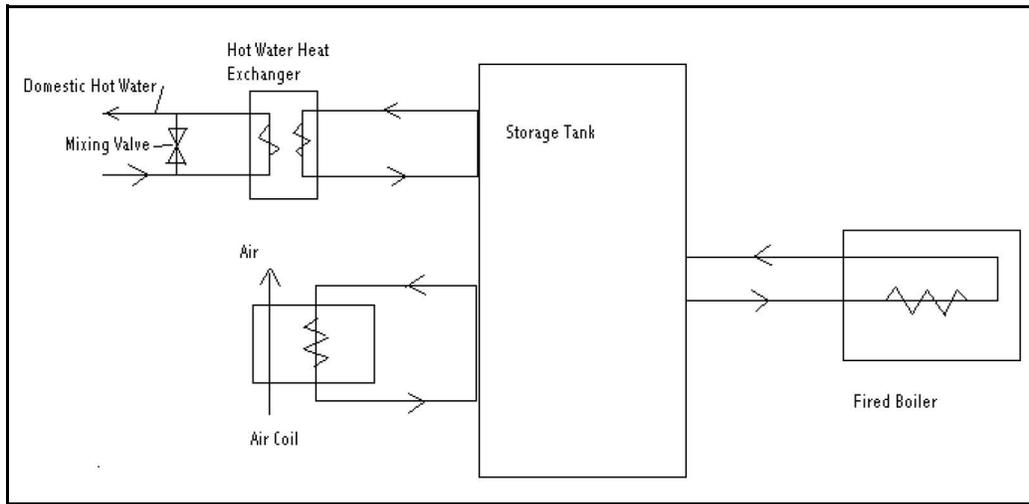
Figure 2   Schematic Space and Water Heating System

Figure 3   Simulator Graphical User Interface