Centrum för solenergiforskning
Solar Energy Research Center

TRNSYS model for Type 210
Pellet stove with liquid heat exchanger

Documentation of model and parameter identification

Preliminary version May 2003

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Abstract
With this model a biofuel stove with liquid heat exhanger is modelled to deliver energy to the ambient air and to a liquid flowstream. The model incorporates two thermal masses for modelling the dynamic behaviour of the stove. The stove is designed to produce a hot gas stream at a user determined rate. The gas will exhange heat with the ambient air, the liquid flowstream and the two masses. The energy rates will depend on the inputs and the state of the stove. The model handles the start-up and stop behaviours of the stove in detail. The model also calculates the CO emitted with the flue gas, thus enabling an assessment of environmentally harmful emissions.The model has two operation modes, one automatic mode which is controlled by temperature differences and where the model controls the start and stop sequences, and one where fuel and combustion air mass flows are set explicitly by inputs to the model. The model may also be used as a burner, delivering a hot gas flowstream to a boiler or tank containing a gas-to-liquid heat exchanger.

1. Introduction

The objective of this project was to evaluate pellet stoves and burners and to make a mathematical model for use in simulations of heating systems.

1.1 Background

Pellet stoves and pellet boilers for domestic heating are becoming increasingly popular and new stove models with liquid heat exchangers have entered the market. Governments are encouraging families to switch from heating by fossil fuels or electricity to heating by renewable sources. Wood pellet is being propagated as an environmentally beneficial heating source by pellet and heating equipment producers.

In order to assess the potential of this fuel it is important to evaluate how much fossil fuel or electricity it is possible to save by using a pellet boiler or stove. In the case of a central heating system, with an oil, gas or electrical boiler serving the whole building, including the DHW (domestic hot water) load this is trivial. Then all the fossil fuel or electricity is saved, except for the electricity needed for running the equipment. Using available data on the efficiency of pellet boilers it is possible to calculate the pellet consumption.

However, when using a pellet stove, often only a part of the heating load can be met. The room where the stove is placed may be completely heated, and adjoining rooms may be only partially heated by the stove, depending on the layout of the building, the properties of the heating and control system, temperature settings and for example whether doors are open or closed. If the pellet stove is equipped with a liquid heat exchanger part of the heating demand and part of the DHW demand may be met by the stove. There are a number of possibilities to connect the heat exchanger to the DHW and heating system.

Compared to oil and gas fired devices, pellet devices pose additional problems. Gas and oil devices have such short start up and close down periods that one may quite safely neglect them when modelling them, both with respect to energy delivery and emissions. It is a matter of a few seconds of transient combustion conditions when starting or stopping the device. However, a pellet burner or stove has a start sequence lasting for at least several minutes and the after-burning phase may last for twenty minutes or more. During these periods a non-neglectable part of the energy is delivered and possibly a major part of the emission of harmful substances may be emitted.

For assessment of the impact of harmful substances, e.g. CO (carbon monoxide) and VOC (volatile organic compounds) caused by biofuels there are only rough overall emission factors and they do not permit studies on how differences in system design, control strategy or stove characteristics influence the emissions.

1.2 Other work

One method to study the yearly performance of a heating system is by computer simulations. The TRNSYS simulation programme (Klein, S.A., *et al.*, 2000) has been extensively used for this purpose, especially for buildings with solar heating. However, very little has been published about systems with biofuel stoves or boilers. The IEA task 26 on solar combisystem has done a numerous simulation studies for many types of systems, but only with gas or oil boilers (Bales, 2003). So far, no simulation studies on buildings with pellet stoves have been published. Considering the rising use of wood pellet and the complexities involved in the modelling of such heating systems, there is a need for computer models of pellet stoves, with and without liquid heat exchangers, in order to perform simulation studies. No dedicated model for a pellet stove, emitting most of its power by convection and radiation is available.

There are presently two ways to model biofuel combustion with TRNSYS, with type 147, a special version of the type 140 storage tank or with the type 170 boiler model, both available from the German company TRANSSOLAR GmbH. None of them is validated or suitable for modelling a stove with liquid heat exchanger. However, the type 140 has been succesfully used together with the model descriped in this report, the type 140 then used for modelling of the convection and storage part of a combined boiler-storage piece of equipment and the type 210 for the combustion part (Nordlander and Persson, 2003).

1.3 Brief model overview

With this model a biofuel stove with liquid heat exhanger is modelled to deliver energy to the ambient air and to a liquid flowstream. The model incorporates two thermal masses for modelling the dynamic behaviour of the stove. The stove is designed to produce a hot gas stream at a user determined rate. The gas will exhange heat with the ambient air, the liquid flowstream and the two masses. The energy rates will depend on the inputs and the state of the stove. The model handles the start-up and stop behaviours of the stove in detail. The model also calculates the CO emitted with the flue gas, thus enabling an assessment of environmentally harmful emissions.

The model has two operation modes, one automatic mode which is controlled by temperature differences and where the model controls the start and stop sequences, and one where fuel and combustion air mass flows are set explicitly by inputs to the model.

The model may also be used as a burner, delivering a hot gas flowstream to a boiler or tank containing a gas-to-liquid heat exchanger.

2. Detailed description of the model

2.1 Overview of the model structure

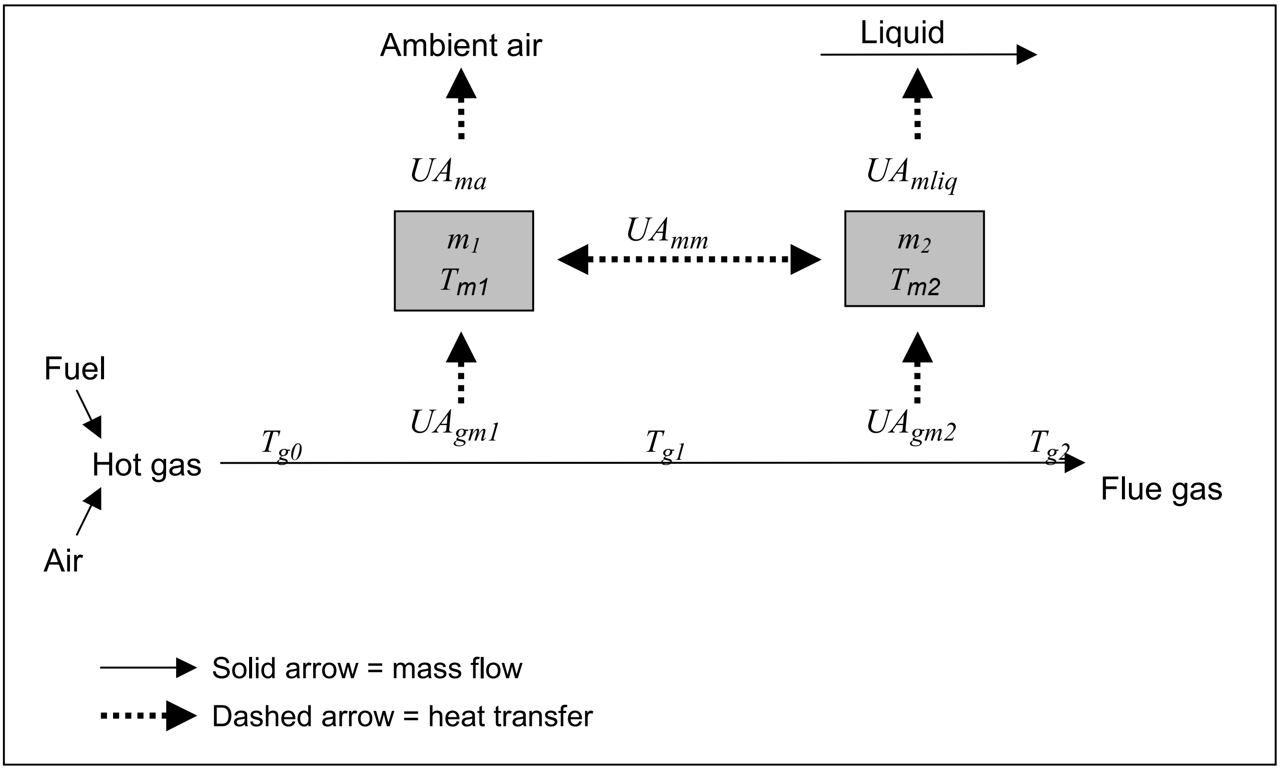

Fig.1. Schematic structure of the wood pellet stove model.

Fig.1 shows the general outline of the model. Fuel and combustion air enter the stove and combust to form a hot gas with mass flow $\dot{m}_g = \dot{m}_f + \dot{m}_a$ and temperature T_{g0}. Energy is transferred from the gas to a first mass, m_1, representing the part of the stove that transfers heat to the ambient air. Having passed m_1 the gas has temperature T_{g1} and heat is transferred to the second mass, m_2, which represents the gas-to-liquid heat exchanger in the stove. Finally the gas leaves the stove at temperature T_g. Heat transfer between the room and mass m_1 is governed by the coefficient UA_{ma} and heat transfer between mass m_2 and the liquid flowstream $\dot{m}_{liq}$ is governed by the coefficient UA_{mliq}. Heat transfer between m_1 and m_2 is governed by the coefficient UA_{mm}.

2.2 Stove control and operation modes

The combustion power P_{cmb} is determined by the minimum and maximum powers P_{max} and P_{min} and the control function γ, such that $P_{cmb} = \gamma P_{max}$. During normal operation P_{cmb} is limited to $P_{min} <= P_{cmb} <= P_{max}$.

The model has two operation modes. When operation mode B_{mod} =1 the model performs predefined service cycles consisting of two start phases, the burning phase and two stop phases . The start and stop phases are initiated by the temperature control or by switches of g between zero and non-zero values. The temperature control turns on and off the stove by means of the set temperatures T_{sta} and T_{stp} and a sensor temperature T_{sens}. When T_{sens} goes below T_{sta} the start phases will be executed, followed by the burning phase. When T_{sens} goes above T_{stp} the stop sequences will be executed. During the burning phase the combustion power is controlled by γ. The start phases will also be initiated when γ goes from zero to a non-zero value. The stop phases will also be initiated when the model is in the burning phase and γ goes from a non-zero value to zero. These two ways of starting and stopping combustion work independently, which allows maximum flexibility but also may cause complicated responses. The user is recommended to use one of the following control strategies at a time:

a) Temperature control with γ always positive: Keep γ at a fixed value for steady-state operation or let γ vary between Q_{cmb}/Q_{min} and Q_{cmb}/Q_{max} for variable power operation. The set temperatures and T_{sens} will turn on and off the stove.
b) Power rate control. Disable the temperature control by assigning suitable values to T_{sta} and T_{stp} or T_{sens}. Turn on and off the stove by switching γ between zero and non-zero values.

It is possible to combine the strategies a) and b), for example to simulate running out of fuel or a power black-out, but the user is recommended to take great care to ensure that the intended behaviour is acheived.

When B_{mod} =2 the combustion power is controlled only by the model inputs for the fuel mass flow $\dot{m}_f$, and combustion air mass flow, $\dot{m}_a$.

2.3 Fuel and combustion

Pellet fuel with wood origin is a well-defined fuel. The Swedish standard SS187120 prescribes the following properties for biofuel pellets:

Lower heating value	> 16.9 MJ/kg total weight
Ash content	< 0.7 %
Water content	< 10 %

The pellet properties influence the model calculations in two ways: firstly, the heating value determines the combustion power, and secondly, the composition of the flue gas influences the heat capacity of the gas and hence the heat transfer processes and the flue gas losses. Most of the pellet fuel consumed in stoves and family-size burners is made from sawdust and shavings. The chemical composition of dry pellet made from these sources varies very little, and the following composition is assumed by the model:

C	50.4 %	of dry weight
O	43.0 %	"
H	6.1 %	"
Ashes	0.4 %	"
Other	0.1 %	"
Water	7.5 %	of total weight
Lower heating value	17.68 MJ/kg total weight	

With these values, assuming complete combustion and 0.74 volume % moisture in the combustion air, a stoichiometric calculation yields the theoretical combustion air ratio A_f of 5.57 kg air / kg fuel. The water content influences the heating value and the theoretical air ratio considerably, and the user is recommended to make sure that the parameter values used the for heating the value and the theoretical air-to-fuel ratio are compatible with each other.

The flue gas composition depends on the fuel properties and the excess air amount. The flue gas heat capacity C_{pg} varies with composition and temperature. It may be calculated accurately by calculating and adding the heat capacities for the constituent gases in proportion to their fractions. The model uses a simple correlation (2) derived from such a calculation:

$$C_{pg} = 1.050304 + 0.000067\ T_g - 0.180080\ [O2_{dry}] - 0.000218\ T_g\ [O2_{dry}] \quad (\text{kJ} / (\text{kg K})),$$

where $[O_{2dry}]$ is the O_2 volume fraction of dry gas. The maximum relative difference between the correlation result and the detailed calculation is 0.0014 in the temperature range between 0 K and 500 K and the $[O2_{dry}]$ range between 0 and 18.4 %. This C_{pg} value represents the average heat capacity between 25 °C and T_g and is thus suitable for calculation of the flue gas losses. C_{pg} will underestimate the real gas heat capacity at the temperatures used for calculation of the heat transfer to the masses m_1 and m_2. This will probably cause only insignificant errors if the heat transfer coefficients are identified using the same correlation. If combustion with a significantly different fuel is to be simulated the equation for calculating C_{pg} must be changed accordingly.

Modern pellet stoves and pellet burners that meet official emission standards have such low levels of emissions of CO and hydrocarbons that the efficiency loss due to uncombusted matter may be neglected. With a normal air factor and at a CO content of 1000 ppm, which is on the order of magnitude of the emission limits, the combustion efficiency is above 99 %. The model assumes the combustion efficiency to be 100 %.

2.4 Power dependance of heat transfer coefficients

In fig.1 the heat transfer coefficient between masses and flowstreams are depicted as constants. The model assumes a linear relationship between combustion power and heat transfer coefficients:

$$UA_{xx} = UA_{xx0} + \gamma UA_{xx1}$$

where $_{xx}$ denotes a particular coefficient.

A number of mechanisms are active in transferring the heat, with varying degrees of temperature dependence at different temperatures. Generally, a higher combustion power implies higher temperatures in flowstreams and masses and thus higher heat transfer coefficients, both for convection and radiation. At constant air surplus, a higher power implies a higher gas mass flow and improved heat transfer. At constant power the air factor will work in different directions, the higher air surplus will on one hand increase turbulence and thus tend to improve convective heat transfer, on the other hand it will lower the gas temperature and thus decrease heat transfer by radiation.

During parameter identification work (Nordlander and Persson, 2003) it was found that it is quite necessary to take into account the power dependency for the gas-to-mass1, gas-to-mass2 transfers and for the mass1-to-room transfers, but not necessarily for the mass1-to-mass2 and mass2-to-liquid transfers. For the sake of conformity and for future work with possibly different stoves and better data quality all heat transfer coefficients are treated the same way, with a linear power dependency.

2.5 Thermal masses

In most normal stoves the combustion takes place behind a glass door, with a visible flame. The hot gas then moves further into the interior and passes the gas-to-liquid heat exhanger, if there is one present. m_1 of the model corresponds to the part of the stove that the gas passes before it reaches the heat exchanger. m_2 corresponds to the heat exchanger. The model does not take into account the thermal mass of any volume of water in the heat exhanger. Having only two masses representing a complex device with a number of different parts made from different materials having different temperatures is of course a great simplification. However, with the kind of data one gets from performance tests of stoves it would probably be difficult to identify more than these two parameters with any significance. If there is a long, uninsulated connection piece connecting the stove to the chimney a separate pipe component might improve the the simulation.

2.6 Heat transfer calculations

The model uses standard textbook logarithmic relations for calculating the temperature changes for the heat transfer processes between combustion gas, the masses, the liquid and the ambient air (Incropera, 1990).

2.7 Combustion start phase

A typical stove has a preset start-phase lasting for a certain time before it starts working under the control of an air thermostat, water thermostat or some other control. Fig.3 shows an example of such a start phase.

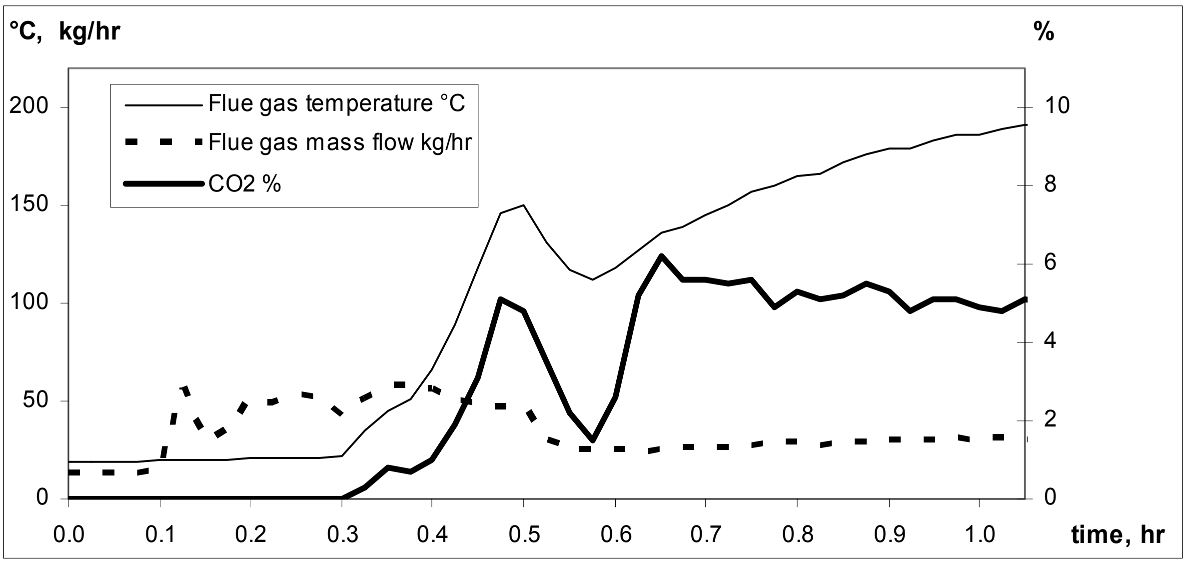

Fig.2. Typical start phase for pellet stove.

a) At 0.1 hr on the time axis of the figure the start phase begins:
- The feeding device feeds a suitable amount, 100-200 g of fuel into the combustion space
- An electric device heats the fuel, directly or by preheating the combustion air
- The combustion air fan starts blowing air onto the fuel
b) At 0.3 hr
- The fuel ignites, as is seen by the start of the temperature rising and the CO2 level rising.
- Shortly after the ignition the stove starts feeding fuel at a regular pace.
c) At 0.5 hr:
- The normal control takes over and adjusts the fan and fuel feed to whatever is required by the circumstances. In this example the control sets the power lower than during the start phase, as seen by the lower air flow and the drop and slower rise of the exhaust gas temperature.

The model performs a two-step start phase in operation mode 1:

1. A first part with duration dt_{sta1}
air flow $\dot{m}_{asta}$ and
electrical power $P_{el} = P_{elsta}$.
The energy delivered by P_{el} is added to the airflow, raising the air temperature. No combustion power is assumed.

2. A second part with duration dt_{sta2}
combustion power $P_{cmb} = P_{cmbsta}$
power factor $\gamma = Q_{cmbsta} / Q_{max}$
air flow $\dot{m}_a = (F_{air0} + \gamma F_{air1}) A_f \, Q_{cmbsta} / H_f$
Electrical power $P_{el} = P_{el0} + \gamma P_{el1}$

In operation mode 2 P_{cmb} *and* $\dot{m}_a$ *and* P_{el} are always set to their respective input values.

2.8 Combustion stop phase

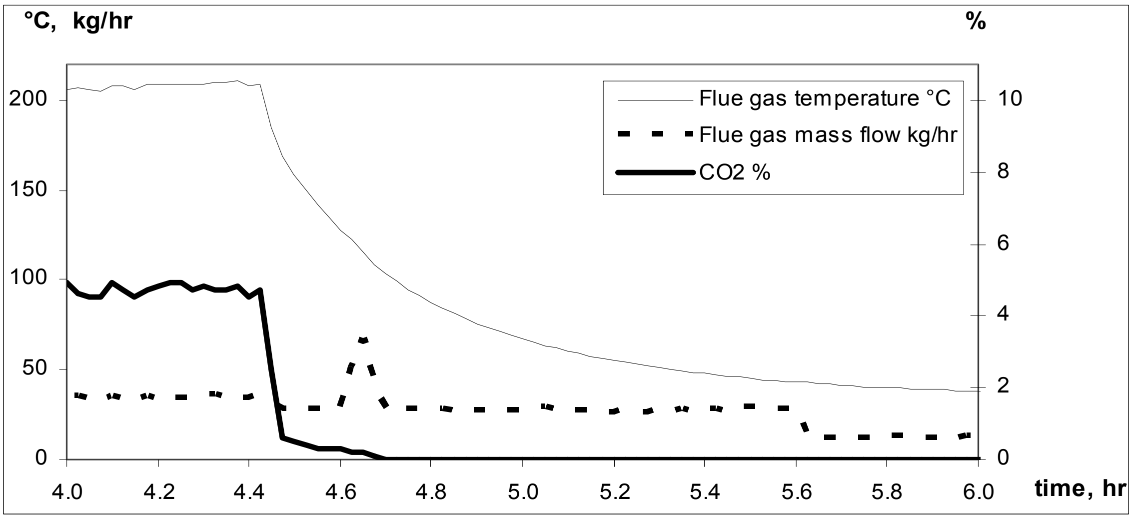

Fig.3. Typical stop phase for pellet stove. The spike in gas flow at 4.65 hr is a short strong

fan blow that occurs every hour (during operation) in order to clean out the combustion chamber from ashes.

A typical stove has a preset stop-phase lasting for a certain time after the pellet feeder has been turned off. Fig.4 shows an example of such a stop phase. Immediately after the pellet feed stops there is a glowing pile of charcoal in the combustion chamber, which may have a considerable size. The glowing char emits CO2 and CO while slowly losing mass and temperature. In order to vent out the gases the fan blows for a certain amount of time after the stop. After the fan stops the gas flow is driven by buoyance forces only and decreases slowly as the stove and the chimney cool down.

The model performs a two-part stop phase in opmode 1:

1. A first part with duration dt_{fanstp} and flue gas flow $\dot{m}_a = \dot{m}_{gfanstp}$. The fan runs at a fixed speed and the combustion power is modeled as exponentially decreasing with time:

$$P_{cmb} = P_{cmbstp} \exp\left(-\left(TIME - t_{stp}\right) / tc_{glow}\right)$$

where P_{cmbstp} is the average combustion power during the five minutes before the stop and tc_{glow} is a time constant for the afterglowing process.

2. A second part which continues until the stove starts again. The combustion power continues to decrease exponentially. The air flow is calculated as

$$\dot{m}_a = \dot{m}_{g50} \sqrt{\left(T_{gpr} - T_{outd}\right) / 50}$$

where $\dot{m}_{g50}$ is the flue gas mass flow at 50 K difference between the gas leaving the stove exhaust, and the outdoor temperature. This relation is reported in Nordlander et al (2003).

2.9 Carbon monoxide emissions

Most stoves allow adjustments of the relation between the air supply and the pelled feed in order to achieve a good compromise between efficiency and low emissions of uncombusted matter. Fig.5 shows the general conditions during combustion as functions of the air factor.

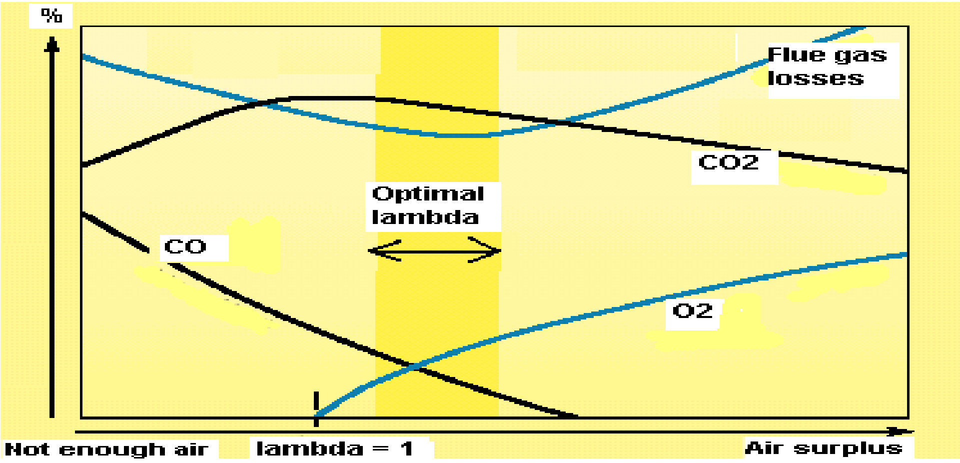

Fig.4. General relations between the air factor λ (lambda), gas content in flue gas and losses for combustion with varying air surplus.

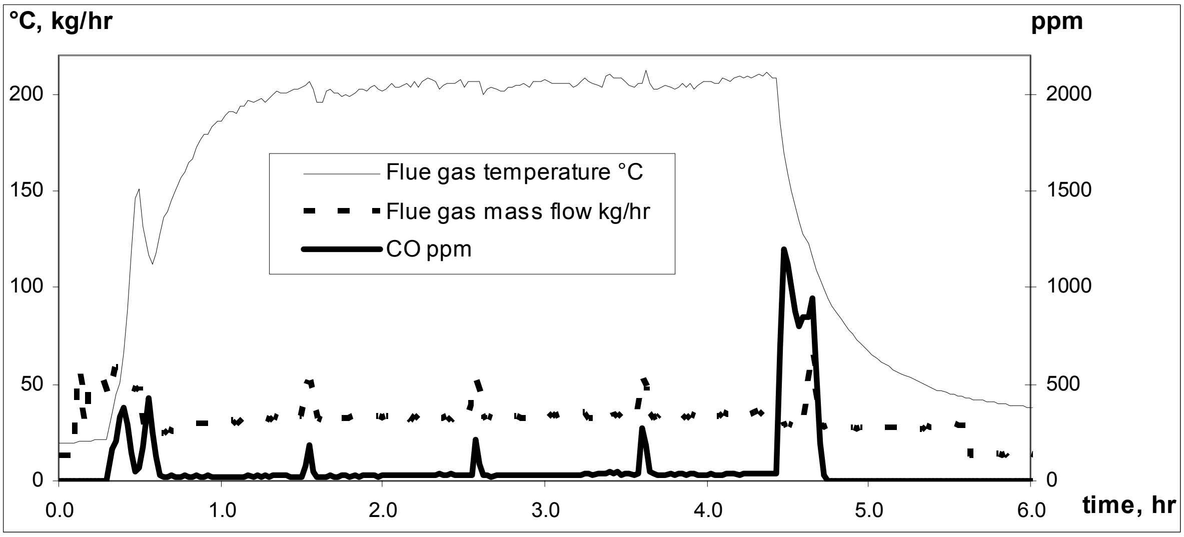

Fig.5. Flue gas temperature, mass flow and CO content for a stove near maximum power.

Figure 6 shows measured data for a combustion cycle with a stove near maximum power. During steady-state operation the CO content is only a fraction of the official emission limit. But during the start and stop phases the emissions are high and occur over a considerable time span, about 15 minutes. Measurements (Nordlander and Persson 2003) have shown that for a given stove these start and stop emissions have a characteristic pattern, rather independent of the settings of the stove.

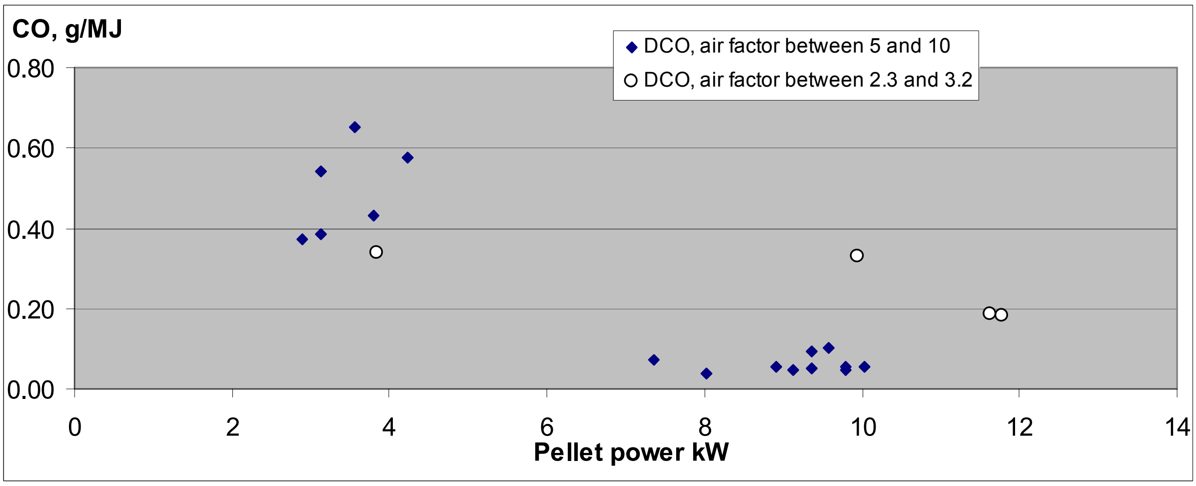

Fig. 6. The relation between CO emission factors and pellet combustion power for one stove with different air factor adjustments. Each point represents the average value for 30 minutes of combustion at a constant power setting.

The relationship between the specific CO emissions and power is not necessarily linear as is demonstrated by fig 7. The emissions depend, among other factors, on oxygen concentration and temperature in the combustion zone, and is thus influenced by both combustion power (since the flame is cooled by its surroundings) and the air surplus. Many stoves operate with air factors well above 2 ($O2 > 10$ %). Measurements indicate that with air factors above 4 the CO emission factor is strongly dependent on power, in a non-linear manner, probably because the flame gets too cold at low combustion power. At lower air factors the emission factor seems to vary only slightly with power, making it safer to assume a linear relationship.

The model calculates the CO emissions as the sum of a power dependent part during normal operation and a lumped constant amount per start and stop. For most stoves the CO emissions are lower at a higher combustion power, so in these cases the emission factor D_{COcmb1} will be negative. The mass flow of CO emitted with the flue gas will be calculated as

$\dot{m}_{CO} = P_{cmb}(D_{CO0} + \gamma D_{CO1})$ during the burning phase.

$\dot{m}_{CO} = m_{COsta} \,/\, DELT$ during a time step when a start is initiated

$\dot{m}_{CO} = m_{COstp} \,/\, DELT$ during a time step when a stop is initiated

In most cases these lumped emissions will cause the simulated CO emissions at start and stop to be higher and shorter than in the real case, but the mass emitted over a full cycle will be correctly calculated.

In order to facilitate emission estimates with different emission factors without running multiple full simulations the following outputs

N_{stacum} Cumulative number of starts
Q_{fcum} Cumulative fuel combustion energy
P_{caw} Average combustion power, energy weighted

from one simulation may be used. The total emissions for the whole simulation will be:

$$m_{COcum} = N_{stacum} (m_{COsta} + m_{COstp}) + Q_{fcum} (D_{CO0} + D_{CO1} P_{caw} / P_{max})$$

Using other values for the CO emission factors in the equation will yield corresponding estimates for the total amount of CO emitted.

2.10 Electrical power consumption

A typical stove consumes electricity for the combustion air fan, the pellet feeder and the control circuitry. The model adds all electric energy as heat to the gas stream before it interacts with mass 1. This is probably a valid assumption for most of the fan energy and the electrical start heater, but less so for the feeder and the circuitry. In the simulation marginally more energy will pass with the exhaust gas than in the real case, but the error is probably quite small. The consumption is modeled as the sum of a constant and a combustion power dependent part:

$$P_{el} = P_{el0} + \gamma P_{el1}$$

3. Scope and limitations of the model

3.1 General considerations

The model is developed for simulation of family-size stoves and burners. The measurements and observations that have led to the formulation of the model were made on the following equipment:

a Swedish 6 kW automatic stove without liquid heat exchanger
an Austrian 10 kW automatic stove with liquid heat exhanger
a German 10 kW automatic stove with liquid heat exhanger
a 25 kW burner mounted on a 750-liter combined storage tank and boiler

The stoves all had glass doors, integral pellet storage for a few days operation and thermostat control with some options for control strategy. Neither stoves nor burner had any automatic control for adjustment of the air factor. The air factor tuning is recommended to be done by a qualified person with proper measuring equipment. Ideally the adjustment should be done at installation and whenever the user switches to a new fuel brand or quality or changes the chimney (or the flue gas channel configuration in the boiler case).

On the market there are more stoves and burners with similar design, combustion and heat exchange principles and control possibilities. These ought to be able to be modeled well by this model, provided proper parameter values are used.

3.2 Time steps

The model has no internal time steps. All calculations are done for a full TRNSYS timestep. For realistic modelling of starts and stops the timeshep should be less than 2 minutes.

3.2 Combustion

The model does not consider the changing composition of the fuel in the combustion chamber during the combustion cycle. At the start more volatile substances are combusted and during the stop phase the glow consists mostly of char. The same applies, but to a lesser degree, to changes in combustion power during operation. Because of differences in the heating value between the different fuel constituents, the relation between fuel mass flow and combustion power is not constant in the real case. The model assumes it to be constant. Over a whole burning cycle the fuel mass and the combustion energy will be correctly calculated though.

3.3 Air leak flow

The empirical data for modelling of the air leak flow through the chimney when the stove is turned off is scarce. The relation used in the model is valid for a light stainless steel chimney of 5 m height. With other chimneys the relation may not work as well. Oil and gas burners have shutters that close the air stream during non-operation, but none of the tested equipment had any shutter. The after-glowing emissions of CO and hydrocarbons would make such a function for pellet combustion more complicated than for an oil or gas burner, but future stoves may be designed with some solution for preventing excessive air leaks. In such a case a new model for the stop sequence and the leak flow may have to be developed.

3.4 CO emissions

Until more thorough analyzes are done on the CO emission factors the user is advised to use them and the resulting total emissions with some caution. The CO emissions at start and stop and at constant power are investigated and are handled by the model. However, at power transients there will occur effects resembling the ones at start and stop, and these are not taken into account by the model. Thus simulations with frequent and large power transient may cause significant underestimations of the CO emissions.

3.5 Modelling of boilers

The model is not validated for a pellet burner integrated with a boiler. The combustion part of the model is probably good enough, but the two-node model of the thermal masses may be to crude for good modelling of the heat losses to the room, the heating of the liquid and the dynamics of the boiler.

In the validation of the model for the pellet burner the model was used only for producing a hot gas which was passed to a model of the storage tank and for the losses from the burner to the ambient air. The heat exchange from the hot gas to the liquid was calculated by an internal heat exchanger in the tank model. The combination of the models produced validation runs with good correspondence with the measured data. The stove model ought to be useful together with a suitable boiler or tank model if used in this fashion.

4. Parameter identification and validation

The parameter identification process and the examples in this section refer to the Wodtke stove. The other two stoves and the burner were analyzed and their parameters identified in a similar manner.

4.1 Tested stoves and burner

PellX 25 kW burner mounted on a 750 liter combined boiler and (solar heating) storage tank
Pitekaminen, stove without liquid heat exchanger
Wodtke Smart, stove with liquid heat exchanger
Sonnenkraft Compello, stove with liquid heat exchanger

4.2 Fuels used

Fuel from four different providers was used. The heating value and the composition of the fuels were analysed twice during the project period. Three fuel types were very similar, but the fourth one (bought during a period of pellet shortage on the market) was of lower quality.

4.3 Measurements

Two kinds of tests were performed:
a) Long time (weeks or months) testing in laboratory with a real load (radiator system) for general observations and recording of validation squences.
b) Special test sequncies (hours and days) with pre-planned variations in power and load

The following data were recorded:
Continuous measurement and logging of:

- -Pellet mass consumption, measured by electronic weight cells
- -Water volume flow in stove and radiator circuits with flow meters
- -Water temperatures with Pt100 sensors
- -Gas and surface temperatures with thermocouples
- -Flue gas flow with Pitot tube in the chimney
- -CO_2, CO, O_2 and NO in dry gas with an automatic extracting on-line gas analyzer

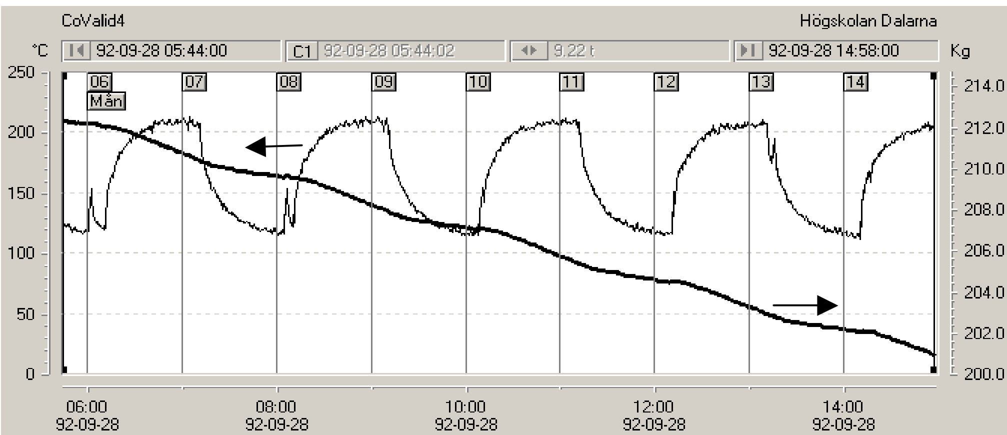

Fig.7. Screen sample of test sequence with combustion power alternating between a high and a low power setting. The thinner curve shows the flue gas temperature at the gas outlet of the stove. The thicker curve shows the weight of the stove including the pellet storage. The rate of the weight decrease is proportional to the combustion power.

The automatic measurements were complemented by:

- Manual surface temperature measurements
- Manual pellet feeding and weight measurements
- Gas flow measurements by mean of plastic bag inflation on the chimney exit and bag deflation on various parts of the burner and indoor parts of the chimney
- Variations in gas flow resistance and chimney configuration
- Variations in cleaning scrutiny and intervals (on the burner)
- Manual measurements of electrical power consumption

The test data data were sampled with one Intab and one HP Hydra logger and collected and stored in a dedicated laboratory PC. The gas analyzer was connected on-line to the PC.

4.4 Parameters directly identified from the measurement data

The following parameters were obtained directly from studies of logged data and using simple conversions:

P_{max}	maximum combustion power
P_{min}	minimum combustion power
λ_0	Air factor at γ=0
λ_1	Air factor, slope
dt_{sta1}	Duration of initial, non-combustion, part of start sequence
dt_{sta2}	Duration of second, combustion, part of start sequence
P_{cmbsta}	Combustion power during second part of start sequence
tc_{glow}	Time constant for stop phase of combustion
dt_{fanstp}	Duration of fan operation after stop
$\dot{m}_{gfanstp}$	Mass flow of flue gas during fan operation after stop
D_{CO0}	CO emission per fuel equivalent, at γ=0
D_{CO1}	CO emission per fuel equivalent, slope

4.5 Parameters identified after refinement of data

The measurement data were refined and elaborated on in Excel worksheets, mostly in order to produce as reliable flue gas volume and mass flow estimates as possible. The flow data were also calibrated with the manual flow measurements. From the refined data it was possible to identify the following parameters:

$\dot{m}_{g50}$	Flue gas leak flow at (T_g - T_{outd})=50 C
m_{COsta}	Mass of lumped CO emission during start phase
m_{COstp}	Mass of lumped CO emission during stop phase

4.6 Parameters identified with the model and the Excel solver tool

The heat transfer part of the model was implemented as a Visual Basic (VB) function that could be called from Excel. Nine test sequencies with 30 minute steady-state operation were selected and the relevant data were averaged over the periods to provide inputs to the VB function. The sequencies represented varying power settings and liquid temperatures. Three sequencies with data from the SP laboratory in Borås were obtained and prepared in the same manner. The 10 UA_{xx} value parameters were entered in cells in the Excel sheet. By "qualified guessing" of the UA_{xx} values and subsequent improvements of them with the Excel Solver tool it was possible to find a set of UA values that minimized an error function for the difference between the measured and calculated energies. Fig 8. shows the thirteen sets of simulated and measured energy rates to liquid, ambient and flue gas. With this method the ten UA_{xx} parameters were identified.

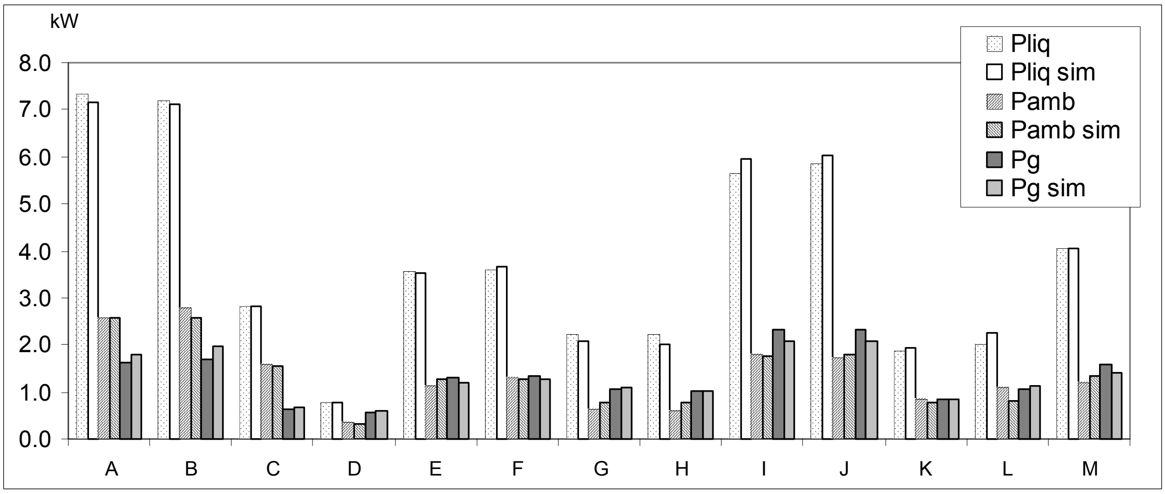

Fig.8. Comparison between measured and simulated values of energy rates for thirteen different steady-state test sequences after optimization of the UA parameters. The three sets A-C are based on measuremnts done by SP, Borås. The ten sets D-M are based on measurements from SERC's combustion laboratory in Borlänge.

4.7 Parameters identified with TRNSYS simulations

The full model was implemented as a Fortran subroutine and linked with TRNSYS. An input data set for TRNSYS was compiled from four test sequencies and simulated. The thermal masses parameters mc_{pm1} and mc_{pm2} were identified by a trial and error process, making the simulated temperature profiles and energy rates during transient periods as similar to the measured ones as possible. The simulations also confirmed that the parameters identified in the earlier stages generated good correspondence.

4.8 Parameter values for the Wodtke stove

The following parameter values are recommended for simulating the Wodtke Smart stove:

P_{max}	maximum combustion power	11.59	kW
P_{min}	minimum combustion power	2.0	kW
UA_{gm10}	UA value between gas and m1 at γ=0	9.19	W/K
UA_{gm11}	UA value between gas and m1, slope	18.4	W/K
UA_{gm20}	UA value between gas and m2 at γ=0	28.1	W/K
UA_{gm21}	UA value between gas and m2, slope	56.2	W/K
UA_{gma0}	UA value between m1 and ambient air at γ=0	3.68	W/K
U_{Agma1}	UA value between m1 and ambient air, slope	0.96	W/K

UA_{mliq0}	UA value between m2 and liquid at γ=0	200	W/K
UA_{mliq1}	UA value between m2 and liquid, slope	180	W/K
UA_{mm0}	UA value between m1 and m2 at γ=0	1.1	W/K
UA_{mm1}	UA value between m1 and m2, slope	0.1	W/K
mc_{pm1}	Thermal mass of mass 1	13	kJ/K
mc_{pm2}	Thermal mass of mass 2	9	kJ/K
dt_{sta1}	Duration of first part of start sequence	0.061	hr
dt_{sta2}	Duration of second part of start sequence	0.287	hr
P_{sta}	Combustion power during 2nd part of start phase	3.41	kW
tc_{exh}	Time constant for glow phase of combustion	0.05	hr
t_{mfanst}	Time duration of fan operation after stop	0.75	hr
$\dot{m}_{gfanstp}$	Mass flow of fan operation after stop	36	kg/hr
$\dot{m}_{g50}$	Flue gas leak flow at (Texh - Toutdoor)=50 C	5	kg/hr
m_{COsta}	Mass of lumped CO emission during start phase	2	g per start
m_{COstp}	Mass of lumped CO emission during stop phase	1.2	g per stop
Pel_0	Electrical power consumption at γ=0	2	W
Pel_1	Electrical power consumption, slope	21	W
P_{elsta}	Electrical power during 1st part of start phase	811	W

Table 1. Recommended fixed values for simulation of the Wodtke Smart stove.

Depending on the air / fuel ratio setting desired during the simulation the user may choose values from the A or B column in Table 2:

		Tuning A	Tuning B	
λ_0	Air factor at γ=0	3.6	9.1	
λ_1	Air factor, slope	-0.97	-6.37	
D_{CO0}	CO emission factor at γ=0	0.48	0.8	g/MJ fuel
D_{CO1}	CO emission factor, slope	-0.078	-0.7	g/MJ fuel

Table 2. Recommended air adjustment dependent values for simulation of the Wodtke smart stove.

Colum A is based on measurement data from a stove adjusted for a normal air surplus, resulting in a total stove efficiency of 86 % and almost constant specific CO emissions over the power spectrum. The air tuning for column B (factory default setting) resulted in a total stove efficiency of 76 % and strongly power dependent CO emissions.

5. Nomenclature

A_f	Theoretical air to fuel mass flow ratio at stoichiometric combustion
B_{mod}	Operation mode
C_{pg}	Average flue gas specific heat
C_{pliq}	Liquid specific heat
D_{CO0}	CO emission per fuel equivalent at γ=0
D_{CO1}	CO emission per fuel equivalent, slope
$DELT$	Simulation time step
dt_{fanstp}	Duration of fan operation after stop
dt_{sta1}	Duration of initial, non-combustion, part of start sequence
dt_{sta2}	Duration of second, combustion, part of start sequence
E	Error sum for convergence testing
F_{air}	Actual air factor
F_{air0}	Air factor, constant part
F_{air1}	Air factor, power dependent part part
H_f	Lower heating value of fuel
i_{start}	Variable indicating timestep when a start occurs
i_{stop}	Variable indicating timestep when a stop occurs
m_{COcum}	Cumulative mass of emitted CO
m_{COsta}	Mass of lumped CO emission during start phase
m_{COstp}	Mass of lumped CO emission during stop phase
mc_{pm1}	Thermal mass of mass 1
mc_{pm2}	Thermal mass of mass 2
m_{fcum}	Cumulative mass of fuel used
$\dot{m}_{gfanstp}$	Mass flow of flue gas during fan operation after stop
$\dot{m}_a$	Combustion air mass flow
$\dot{m}_g$	Flue gas mass flow
$\dot{m}_f$	Fuel mass flow
$\dot{m}_{liq}$	Liquid mass flow
$\dot{m}_{asta}$	Combustion air mass flow during second part of start phase
$\dot{m}_{g50}$	Flue gas leak flow at (T_g - T_{outd})=50 C
$\dot{m}_{CO}$	Mass flow of CO in exhaust gas
N_{stacum}	Cumulative number of starts
P_{amb}	Power to ambient air in room
P_{caw}	Average combustion power, energy weighted
P_{cmb}	Actual combustion power
P_{cmbsta}	Combustion power during second part of start phase
P_{cmbstp}	Combustion power during the five minutes before a stop
P_{el}	Actual electrical power consumption
P_{el0}	Electrical power consumption, constant part
P_{el1}	Electrical power consumption, power dependent part part

P_{elsta}	Electrical power consumption during first part of start phase
P_{g2}	Power to exhaust gas
P_{gm1}	Power from combustion gas to m1
P_{gm2}	Power from combustion gas to m2
P_{liq}	Power to liquid through heat exchanger
P_{m1m2}	Power from m1 to m2
P_{max}	Maximum combustion power
P_{min}	Minimum combustion power
Q_f	Fuel combustion energy developed during timestep
Q_{fcum}	Cumulative fuel combustion energy
Q_{fcumpr}	Cumulative fuel energy at end of previous timestep
T_a	Temperature of combustion air
tc_{glow}	Time constant for stop phase of combustion
t_{fanstp}	Simulation time when the fan stops in the stop phase
T_{g0}	Temperature of combustion gas before meeting m1
T_{g1}	Temperature of combustion gas before meeting m2
T_{g2}	Flue gas temperature
T_{g2pr}	Flue gas temperature at end of previous timestep
$TIME$	simulation time at the start of the current time step
T_{lqi}	Temperature of liquid entering heat exchanger
T_{lqo}	Temperature of liquid out of heat exchanger
T_{m1}	Temperature of mass 1 (connected to ambient air)
T_{m1a}	Intermediate temperature in convergence loop
T_{m1pr}	Temperature of mass 1 at end of previous timestep
T_{m2}	Temperature of mass 2 (liquid heat exchanger)
T_{m2a}	Intermediate temperature in convergence loop
T_{m2pr}	Temperature of mass 2 at end of previous timestep
T_{outd}	Outdoor temperature
T_{room}	Temperature around stove to which Qamb occurs
T_{sens}	Temperature of sensor for temperature control
T_{senspr}	Sensor temperature at end of previous timestep
T_{sta}	Set temperature for combustion start
t_{sta}	Simulation time when the stove turns on
t_{sta1}	Simulation time at the end of the first part of the start phase
t_{sta2}	Simulation time at the end of the second part of the start phase
T_{stp}	Set temperature for combustion stop
t_{stp}	Simulation time when the stove turns off
UA_{gm1}	Actual UA value between gas and m1
UA_{gm10}	UA value between gas and m1, constant part
UA_{gm11}	UA value between gas and m1, power dependent part part
UA_{gm2}	Actual UA value between gas and m2
UA_{gm20}	UA value between gas and m2, constant part
UA_{gm21}	UA value between gas and m2, power dependent part part

UA_{ma}	Actual UA value between m1 and ambient air
UA_{ma0}	UA value between m1 and ambient air, constant part
UA_{ma1}	UA value between m1 and ambient air, power dependent part part
UA_{mliq}	Actual UA value between m2 and liquid
UA_{mliq0}	UA value between m2 and liquid, constant part
UA_{mliq1}	UA value between m2 and liquid, power dependent part part
UA_{mm}	Actual UA value between m1 and m2
UA_{mm0}	UA value between m1 and m2, constant part
UA_{mm1}	UA value between m1 and m2, power dependent part part
X_{caw}, X_{cawpr}	Intermediate terms in average power weighting
X_{phase}	Operation phase during timestep
γ	Ratio of actual combustion power to maximum power
γ_{pr}	γ at end of previous timestep

6. Mathematical Description

At the beginning of the simulation the following variables are initialized (these variables are declared STATIC and retain their values between iterations and timesteps until changed by the model):

$t_{sta} = t_{sta1} = t_{sta2} = t_{stp} = t_{fanstp} = -1$
$T_{senspr} = T_{g2pr} = T_{m1pr} = T_{m2pr} = 0$
$Q_{fcum} = Q_{fcumpr} = P_{caw} = X_{caw} = X_{cawpr} = m_{fcum} = 0$
$N_{stacum} = N_{stacumpr} = 0$

For every timestep:

$i_{start} = i_{stop} = 0$

In operation mode 1 ($B_{mod} = 1$) :

If ($T_{senspr} > T_{sta}$ and $T_{sens} \le T_{sta}$) or ($\gamma_{pr} = 0$ and $\gamma > 0$) then

$i_{start} = 1$
$t_{sta} = TIME$
$t_{sta1} = TIME + dt_{sta1}$
$t_{sta2} = TIME + dt_{sta1} + dt_{sta2}$
$t_{stp} = t_{fanstp} = TIME + 999999$

If ($t_{sta} > 0$) and (($T_{senspr} \le T_{stp}$ and $T_{sens} > T_{stp}$) or ($\gamma_{pr} > 0$ and $\gamma = 0$)) then

$i_{stop} = 1$
$t_{sta} = t_{sta1} = t_{sta2} = 0$
$t_{stp} = TIME$
$t_{fanstp} = TIME + dt_{fanstp}$
P_{cmbstp} is calculated as the average of P_{cmb} over the last five minutes.

If ($t_{sta} < 0$) then

$P_{cmb} = 0$
$\dot{m}_f = 0$
If ($T_{gpr} > T_{outd}$) then $\dot{m}_a = \dot{m}_{g50}\sqrt{(T_{gpr} - T_{outd})/50}$) else $\dot{m}_a = 0$
$P_{el} = 0$

If $t_{sta} \le TIME < t_{sta1}$ then

$P_{cmb} = 0$
$\dot{m}_f = 0$
$\dot{m}_a = \dot{m}_{asta}$
$P_{el} = P_{elsta}$

If $t_{sta1} \le TIME < t_{sta2}$ then

$P_{cmb} = P_{cmbsta}$

$\dot{m}_f = P_{cmb} / H_f$
$\lambda = \lambda_0 + \gamma \lambda_1$
$\dot{m}_a = \dot{m}_f \; \lambda \; A_f$
$P_{el} = P_{elsta}$

If $t_{sta2} \leq TIME < t_{stp}$ then
$P_{cmb} = \gamma P_{max}$
$\dot{m}_f = P_{cmb} / H_f$
$\dot{m}_a = \dot{m}_f \; (\lambda_0 + \gamma \lambda_1) \; A_f$
$P_{el} = P_{el0} + \gamma \; P_{el1}$

If $t_{stp} \leq TIME < t_{fanstp}$ then
$P_{cmb} = P_{cmbstp} \exp(-(TIME - t_{stp}) / tc_{glow})$
$\dot{m}_f = P_{cmb} / H_f$
$\dot{m}_a = \dot{m}_{gfanstp}$
$P_{el} = (P_{el0} + P_{el1}) \; \dot{m}_{gfanstp} \; / \; (\dot{m}_f \; (\lambda_0 + \lambda_1) \; A_f)$

If $t_{fanstp} \leq TIME$ then
$P_{cmb} = P_{cmbstp} \exp(-(TIME - t_{stp}) / tc_{glow})$
$\dot{m}_f = P_{cmb} / H_f$
If ($T_{gpr} > T_{outd}$) then $\dot{m}_a = \dot{m}_{g50} \sqrt{(T_{gpr} - T_{outd}) / 50}$) else $\dot{m}_a = 0$
$P_{el} = P_{el0}$

<u>In operation mode 2</u> ($B_{mod} = 2$) :
$P_{cmb} = \dot{m}_f \; H_f$
If $P_{cmbpr} = 0$ and $P_{cmb} > 0$ $\quad i_{start} = 1$
If $P_{cmbpr} > 0$ and $P_{cmb} = 0$ $\quad i_{stop} = 1$

<u>In all operation modes</u> ($B_{mod} = 1$ or 2) :
If ($\dot{m}_f = 0$) or ($\dot{m}_a = 0$) then
$O2_{dry} = 0.21$
else
$\lambda = \dot{m}_a / (\dot{m}_f H_f)$
$O2_{dry} = 0.21 \; (\lambda - 1) / \lambda$

$\dot{m}_g = \dot{m}_f + \dot{m}_a$
$\gamma = P_{cmb} / P_{max}$

$UA_{gm1} = UA_{gm10} + \gamma UA_{gm11}$

$UA_{gm2} = UA_{gm20} + \gamma UA_{gm21}$
$UA_{ma} = UA_{ma0} + \gamma UA_{ma1}$
$UA_{mliq} = UA_{mliq0} + \gamma UA_{mliq1}$
$UA_{mm} = UA_{mm0} + \gamma UA_{mm1}$

$T_{m1} = T_{m1pr}$
$T_{m2} = T_{m2pr}$
$T_{g2} = T_{g2pr}$

$E = 100$
DO WHILE ($E > 0.001$)
$T_{m1a} = (T_{m1pr} + T_{m1}) / 2$
$T_{m2a} = (T_{m2pr} + T_{m2}) / 2$
$C_{pg} = 1.046661 + 0.00016844\ T_g - 0.168154\ O_{2dry} - 0.00054628\ T_g * O_{2dry}$
If $\dot{m}_g = 0$ $T_{g0} = T_a$
If $\dot{m}_g <> 0$ $T_{g0} = T_a + (P_{cmb} + P_{el}) / (\dot{m}_g C_{pg})$
$T_{g1} = T_{g0} + (T_{m1} - T_{g0}) \exp(-\dot{m}_g C_{pg} / UA_{gm1})$
$T_{g2} = T_{g1} + (T_{m2} - T_{g1}) \exp(-\dot{m}_g C_{pg} / UA_{gm2})$
$T_{lqo} = T_{lqi} + (T_{m2} - T_{lqi}) \exp(-\dot{m}_{liq} C_{pliq} / UA_{mliq})$
$P_{gm1} = \dot{m}_g C_{pg} (T_{g0} - T_{g1})$
$P_{gm2} = \dot{m}_g C_{pg} (T_{g1} - T_{g2})$
$P_{liq} = \dot{m}_{liq} C_{pliq} (T_{lqo} - T_{lqi})$
$P_{amb} = UA_{ma} (T_{m1} - T_{room})$
$P_{m1m2} = UA_{mm} (T_{m1} - T_{m2})$
$T_{m1} = T_{m1pr} + DELT\ (P_{gm1} - P_{amb} - P_{m1m2}) / mc_{pm1}$
$T_{m2} = T_{m2pr} + DELT\ (P_{gm2} - P_{liq} + P_{m1m2}) / mc_{pm2}$
$E = \text{ABS}\ (T_{m1a} - (T_{m1pr} + T_{m1}) / 2) + \text{ABS}\ (T_{m2a} - (T_{m2pr} + T_{m2}) / 2) + \text{ABS}(T_{g2} - T_{g2pr})$

$P_{g2} = P_{cmb} + P_{el} - P_{gm1} - P_{gm2}$
$Q_f = P_{cmb}\ DELT$
$m_{COcum} = (i_{start}\, m_{COsta} + i_{stop}\, m_{COstp}) / DELT + Pcmb\ (em_{CO0} + \gamma em_{CO1})$

$Q_{fcum} = Q_{fcumpr} + Q_{fu}$
$X_{caw} = X_{cawpr} + P_{cmb}\, Q_{fu}$
$P_{caw} = X_{cmb} / Q_{fcum}$
$N_{stacum} = N_{stacumpr} + i_{start}$
$m_{fcum} = Q_{fcum} / H_f$

7. TRNSYS Component Configuration:

PARAMETER		DESCRIPTION	UNIT
1	B_{mod}	Operation mode	
	1	Control by power input and air factor (inputs 1 and 2)	
	2	Direct control by fuel and air mass flows (inputs 1 and 2)	
2	A_f	Air to fuel mass flow ratio at $\lambda = 1$	
3	H_f	Lower heating value of fuel	kJ/ kg
4	C_{pliq}	Specific heat of liquid	kJ/ (kg K)
5	m_{mcpm1}	Thermal mass of mass 1	kJ/K
6	m_{cpm2}	Thermal mass of mass 2	kJ/K
7	P_{max}	maximum combustion power	kJ/hr
8	P_{min}	minimum combustion power	kJ/hr
9	P_{cmbsta}	Combustion power during second part of start phase	kJ/hr
10	P_{elsta}	Electrical power consumption during 1st part of start phase	kJ/hr
11	P_{el0}	Electrical power consumption, constant part	kJ/hr
12	P_{el1}	Electrical power consumption, power dependent part part	kJ/hr
13	dt_{sta1}	Initial, non-combustion, part of start sequence	hr
14	dt_{sta2}	Second, combustion, part of start sequence	hr
15	dt_{fanst}	Time duration of fan operation after stop	hr
16	tc_{glow}	Time constant for stop phase of combustion	hr
17	$\dot{m}_{gfanstp}$	Mass flow of flue gas during fan operation after stop	kg/hr
18	$\dot{m}_{g50}$	Flue gas leak flow at (Texh - Toutdoor)=50 C	kg/hr
19	mcp_{m1}	Thermal mass of mass 1	kJ/K
20	mcp_{m2}	Thermal mass of mass 2	kJ/K
21	UA_{gm10}	UA value between gas and m1, fixed	kJ/(hr K)
22	UA_{gm11}	UA value between gas and m1, slope	kJ/(hr K)
23	UA_{gm20}	UA value between gas and m2, fixed	kJ/(hr K)
24	UA_{gm21}	UA value between gas and m2, slope	kJ/(hr K)
25	UA_{gma0}	UA value between m1 and ambient air, fixed	kJ/(hr K)
26	UA_{gma1}	UA value between m1 and ambient air, slope	kJ/(hr K)
27	UA_{mliq0}	UA value between m2 and liquid, fixed	kJ/(hr K)
28	UA_{mliq1}	UA value between m2 and liquid, slope	kJ/(hr K)
29	UA_{mm0}	UA value between m1 and m2, fixed	kJ/(hr K)
30	UA_{mm1}	UA value between m1 and m2, slope	kJ/(hr K)
31	D_{CO0}	CO emission factor at $\gamma = 0$	g/kJ fuel
32	D_{CO1}	CO emission factor, slope	g/kJ fuel
33	m_{COsta}	Lumped CO emission during start phase	g per start
34	m_{COstp}	Lumped CO emission during stop phase	g per stop

INPUT		DESCRIPTION	
Operation mode (parameter 3) = 1		Power fraction and air factor, temp control	
1	γ	Fraction of maximum power	
4	T_{sta}	Set temperature for combustion start	° C
5	T_{stp}	Set temperature for combustion stop	° C
6	T_{sens}	Temperature of sensor for temperature control	° C
Operation mode (parameter 3) = 2		Direct control by fuel and air flows	
1	$\dot{m}_f$	Fuel mass flow	kg/hr
2	$\dot{m}_a$	Combustion air mass flow	kg/hr
3	P_{el}	Electrical power supplied to stove	kJ/hr
4	-	not used	
5	-	not used	
6	-	not used	
All modes:			
7	T_{room}	Ambient temperature around stove	° C
8	T_{outd}	Outdoor temperature	° C
9	T_a	Temperature of combustion air	° C
10	$\dot{m}_{liq}$	Mass flow of liquid entering heat exchanger	kg/hr
11	T_{lqi}	Temperature of liquid entering heat exchanger	° C

OUTPUT		DESCRIPTION	
1	P_{cmb}	Combustion power	kJ/hr
2	P_{el}	Electrical power used	kJ/hr
3	P_{amb}	Power to ambient air in room	kJ/hr
4	P_{liq}	Power to liquid through heat exchanger	kJ/hr
5	P_{exh}	Power to exhaust gas	kJ/hr
6	T_{m1}	Temperature of mass 1 (connected to ambient air)	° C
7	T_{m2}	Temperature of mass 2 (liquid heat exchanger)	° C
8	$\dot{m}_f$	Fuel mass flow	kg/hr
9	$\dot{m}_a$	Combustion air mass flow	kg/hr
10	$\dot{m}_{liq}$	Liquid mass flow	kg/hr
11	T_{lqo}	Temperature of liquid out of heat exchanger	° C
12	$\dot{m}_g$	Flue gas mass flow	kg/hr
13	T_g	Flue gas temperature	° C
14	C_{pexh}	Flue gas specific heat	kJ/(kg K)
15	$\dot{m}_{CO}$	Mass flow of CO in exhaust gas	kg/hr
16	N_{stacum}	Cumulative number of starts	
17	m_{fcum}	Cumulative mass of fuel used	kg
18	m_{COcum}	Cumulative mass of emitted CO	kg
19	Q_{caw}	Average combustion power, energy weighted	kJ/hr
20	X_{phase}	Operation phase during timestep	

0 = off and no combustion
1 = start phase 1
2 = start phase 2
3 = burning phase
4 = afterglowing phase with fan operation
5 = afterglowing phase without fan operation

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Appendix A
Fortran listing of the type 210 TRNSYS model of a pellet stove

```
      SUBROUTINE TYPE210(TIME,XIN,OUT,T,DTDT,PAR,INFO,ICNTRL,*)
C*********************************************************************
C  AUXILIARY PELLET HEATER.
C   2003-05-18 -- SN Type 210, with start, stop and CO
C   2003-03-02 -- SN Type 209, with two masses
C   2002-05-07 -- SN Converted type 6 to pellet burner model
C*********************************************************************
C*********************************************************************
      INCLUDE '\trnsys15\include\param.inc'
      INTEGER NPAR, NINP, NOUT, NSTO, I
      PARAMETER (NPAR=34)
      PARAMETER (NINP=11)
      PARAMETER (NOUT=22)
      PARAMETER (NSTO=40)

      DOUBLE PRECISION XIN,OUT
      REAL TIME,T,DTDT,PAR
    INTEGER INFO, ICNTRL
      DIMENSION XIN(NINP),OUT(NOUT),T(1),DTDT(1),PAR(NPAR),INFO(15)
      CHARACTER*3 YCHECK(NINP),OCHECK(NOUT)

      REAL      TIME0, TFINAL, DELT,IWARN
    COMMON /SIM/ TIME0, TFINAL, DELT,IWARN
    INTEGER NSTORE, IAV
      REAL S
    COMMON /STORE/ NSTORE,IAV,S(NUMSTR)

C   PARAMS
    REAL Bmod   !   1   Operation mode
C          1=Ctrl by power input and air factor (inputs 1,2 and 3)
C          2=Direct ctrl by fuel and air mass flows (inputs 1 and 2)
    REAL Af     !   2   Air to fuel mass flow ratio at lbd=1
    REAL Hf     !   3   Lower heating value of fuel                kJ/ kg
    REAL Cpliq  !   4   Specific heat of liquid                    kJ/ (kg
K)
    REAL mcpm1  !   5   Thermal mass of mass 1                     kJ/K
    REAL mcpm2  !   6   Thermal mass of mass 2                     kJ/K
    REAL Pmax   !   7   maximum combustion power               kJ/hr
    REAL Pmin   !   8   minimum combustion power               kJ/hr
    REAL Pcmbsta  !9   Comb power second part of start phase   kJ/hr
    REAL Pelsta !   10  Electr power during 1st part of start phase  kJ/hr

    REAL Pe0    !   11  Electr power consumption at g=0            kJ/hr
    REAL Pe1    !   12  Electr power consumption at g=1            kJ/hr
    REAL dtsta1 !   13  Initial, non-comb, part of start sequence hr
    REAL dtsta2 !   14  Second, comb, part of start sequence      hr
    REAL dtfstp !   15  Time duration of fan oper after stop      hr
    REAL tcglow !   16  Time constant for afterglow phase of comb hr
    REAL mfgfanstp !17 Mass fl of flue gas during fan op after stp   kg/hr
    REAL mfg50  !   18  Flue gas leak flow at (Texh-Toutdoor)=50 C   kg/hr
    REAL free1  !   19  not used
    REAL free2  !   20  not used
    REAL UAgm10 !   21  UA value between gas and m1 at g=0        kJ/(hr K)
    REAL UAgm11 !   22  UA value between gas and m1 at g=1        kJ/(hr K)
    REAL UAgm20 !   23  UA value between gas and m2 at g=0        kJ/(hr K)
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    REAL UAgm21 !   24  UA value between gas and m2 at g=1        kJ/(hr K)
    REAL UAma0  !   25  UA value between m1 and ambient air at g=0    kJ/(hr
K)
    REAL UAma1  !   26  UA value between m1 and ambient air at g=1    kJ/(hr
K)
    REAL UAmlq0 !   27  UA value between m2 and liquid at g=0     kJ/(hr K)
    REAL UAmlq1 !   28  UA value between m2 and liquid at g=1     kJ/(hr K)
    REAL UAmm0  !   29  UA value between m1 and m2 at g=0         kJ/(hr K)
    REAL UAmm1  !   30  UA value between m1 and m2 at g=1         kJ/(hr K)
    REAL DCO0   !   31  CO emission factor at g=0                 g/kJ fuel
    REAL DCO1   !   32  CO emission factor at g=1                 g/kJ fuel
    REAL mCOsta !   33  Lumped CO emission during start phase g per start
    REAL mCOstp !   34  Lumped CO emission during stop phase  g per stop


C       INPUTS
C   Operation mode (parameter 1) = 1  Power fraction and air factor, temp
control
    REAL g      !   1   Fraction of maximum power
    REAL lbd0   !   2   Air factor, constant
    REAL lbd1   !   3   Air factor, slope
    REAL Tmpsta !   4   Set temperature for combustion start          °C
    REAL Tmpstp !   5   Set temperature for combustion stop               °C
    REAL Tsens  !   6   Temperature of sensor for temperature control °C
C   Operation mode (parameter 1) = 2  Direct control by fuel and air flows
    REAL mff    !   1   Fuel mass flow                                kg/hr
    REAL mfa    !   2   Combustion air mass flow                      kg/hr
    REAL Pel    !   3   Electrical power supplied to stove            kJ/hr
C                   4   not used
C                   5   not used
C                   6   not used
C   All modes:
    REAL Troom  !   7   Ambient temperature around stove              °C
    REAL Toutd  !   8   Outdoor temperature                               °C
    REAL Ta     !   9   Temperature of combustion air                 °C
    REAL mflq   !   10  Mass flow of liquid entering heat exchanger
    kg/hr
    REAL Tlqi   !   11  Temperature of liquid entering heat exchanger °C


C   OUTPUT      DESCRIPTION
    REAL Pcmb   !   1   Combustion power                              kJ/hr
C   REAL Pel    !   2   Electrical power used                         kJ/hr
    REAL Pamb   !   3   Power to ambient air in room                  kJ/hr
    REAL Pliq   !   4   Power to liquid through heat exchanger
    kJ/hr
    REAL Pg     !   5   Power to exhaust gas                          kJ/hr
    REAL Tm1    !   6   Temperature of mass 1 (connected to amb air)  ° C
    REAL Tm2    !   7   Temperature of mass 2 (liquid heat exchanger) ° C
C   REAL mff    !   8   Fuel mass flow                                kg/hr
C   REAL mfa    !   9   Combustion air mass flow                      kg/hr
C   REAL mflq   !   10  Liquid mass flow                              kg/hr
    REAL Tlqo   !   11  Temperature of liquid out of heat exchanger      ° C
    REAL mfg    !   12  Flue gas mass flow                            kg/hr
    REAL Tg2    !   13  Flue gas temperature                          ° C
    REAL Cpg    !   14  Flue gas specific heat                        kJ/(kg
K)
    REAL mfCO   !   15  Mass flow of CO in exhaust gas            kg/hr
    REAL Nstacum !  16  Cumulative number of starts

    REAL mfcum  !   17  Cumulative mass of fuel used              kg
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      REAL mCOcum !   18  Cumulative mass of emitted CO           kg
      REAL Pcaw   !   19  Average combustion power, energy weighted kJ/hr
      REAL Opph   !   20  Operation phase during timestep
C                 !       -1= Opmode=2, direct control
C                 !       0 = off and no combustion
C                 !       1 = start phase 1
C                 !       2 = start phase 2
C                 !       3 = burning phase
C                 !       4 = afterglowing phase with fan operation
C                 !       5 = afterglowing phase without fan operation

C     Help variables
      INTEGER  IST     !   Start of storage space in S array
      INTEGER istart, istop
      REAL    Pcmbpr, Pavgm, Pavgmpr, Xpavg
      REAL    Tm1pr,Tm2pr
      REAL    Nstacumpr
      REAL    mfcumpr
      REAL    mCOcumpr
      REAL    Xcawpr
      REAL    Tsenspr
      REAL    Pcmbstp
      REAL    gpr
      REAL    gtmp
      REAL    tsta0
      REAL    tsta1
      REAL    tsta2
      REAL    tstp
      REAL    tfanstp
      REAL    O2dry, lbd
      REAL    UAgm1,UAgm2,UAma,UAmliq,UAmm
      REAL    Tm1a, Tm2a
      REAL    E
      REAL    Tg0, Tg1, Tg2pr
      REAL    Pgm1, Pgm2, Pm1m2
      REAL    mf
      REAL    Xcaw
      REAL    mfcumw,mfcumwpr

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      IF (INFO(7).EQ.-1) THEN              ! First call in simulation
        INFO(6)=NOUT                    ! Number of outputs
        INFO(10)=NSTO                   ! Allocate storage
        CALL TYPECK(1,INFO,NINP,NPAR,0) ! No of inputs and params

      DATA YCHECK/'DM1','DM1','DM1','DM1','DM1','DM1','DM1','DM1',
      4           'DM1','DM1','DM1'/
      DATA OCHECK/'DM1','DM1','DM1','DM1','DM1','DM1','DM1','DM1',
      1           'DM1','DM1','DM1','DM1','DM1','DM1','DM1','DM1',
      2           'DM1','DM1','DM1','DM1','DM1','DM1'/
        CALL RCHECK(INFO,YCHECK,OCHECK)

        IST=INFO(10)       !   Storage start in S array for this unit
        DO I=IST, IST+NSTO-1 ,1
            S(I)=0
        END DO
        S(IST+24)=-1   !tsta0
        S(IST+25)=-1   !tsta1
        S(IST+26)=-1   !tsta2
        S(IST+27)=-1   !tstp
        S(IST+28)=-1   !tfanstp
```

```
        S(IST+29)=0    !Pcmbstp
        DO I=1, NOUT
            OUT(I)=0
        END DO
        RETURN 1
    END IF

    IST=INFO(10)               !   Storage start in S array for this unit
    IF (INFO(7).EQ.0) THEN     ! First iteration in timestep
C       Save values from previous time step
        S(IST+2)=S(IST+1)  !   Pcmbpr
        S(IST+4)=S(IST+3)  !   Tm1pr
        S(IST+6)=S(IST+5)  !   Tm2pr
        S(IST+8)=S(IST+7)  !   Tg2pr
        S(IST+10)=S(IST+9) !   Nstacumpr
        S(IST+12)=S(IST+11)    !   mfcumpr
        S(IST+14)=S(IST+13)    !   mCOcumpr
        S(IST+16)=S(IST+15)    !   Xcawpr
        S(IST+18)=S(IST+17)    !   Tsenspr
        S(IST+20)=S(IST+19)    !   gpr
        S(IST+22)=S(IST+21)    !   Pavgm avg Pcmb last 5 minutes
        S(IST+24)=S(IST+23)    !   mfcumwpr for avg weighting
    END IF

C       Recall values
    Pcmbpr   =S(IST+2)
    Tm1pr    =S(IST+4)
    Tm2pr    =S(IST+6)
    Tg2pr   =S(IST+8)
    Nstacumpr=S(IST+10)
    mfcumpr  =S(IST+12)
    mCOcumpr =S(IST+14)
    Xcawpr   =S(IST+16)
    Tsenspr  =S(IST+18)
    gpr      =S(IST+20)
    Pavgmpr  =S(IST+22)
    mfcumwpr =S(IST+24)

    tsta0    =S(IST+31)
    tsta1    =S(IST+32)
    tsta2    =S(IST+33)
    tstp     =S(IST+34)
    tfanstp  =S(IST+35)
    Pcmbstp  =S(IST+36)

C   PARAMS
    Bmod    =PAR(1)
    Af      =PAR(2)
    Hf      =PAR(3)
    Cpliq   =PAR(4)
    mcpm1   =PAR(5)
    mcpm2   =PAR(6)
    Pmax    =PAR(7)
    Pmin    =PAR(8)
    Pcmbsta =PAR(9)
    Pelsta  =PAR(10)
    Pe0     =PAR(11)
    Pe1     =PAR(12)
    dtsta1  =PAR(13)
    dtsta2  =PAR(14)
    dtfstp  =PAR(15)
```

```
      tcglow  =PAR(16)
      mfgfanstp   =PAR(17)
      mfg50   =PAR(18)
      free1   =PAR(19)
      free2   =PAR(20)
      UAgm10  =PAR(21)
      UAgm11  =PAR(22)
      UAgm20  =PAR(23)
      UAgm21  =PAR(24)
      UAma0   =PAR(25)
      UAma1   =PAR(26)
      UAmlq0  =PAR(27)
      UAmlq1  =PAR(28)
      UAmm0   =PAR(29)
      UAmm1   =PAR(30)
      DCO0    =PAR(31)
      DCO1    =PAR(32)
      mCOsta  =PAR(33)
      mCOstp  =PAR(34)

C     INPUTS
      Troom    =xin(7)
      Toutd    =xin(8)
      Ta       =xin(9)
      mflq     =xin(10)
      Tlqi     =xin(11)

      istart=0
      istop =0

      IF  (Bmod==1) THEN
          g       =xin(1)
          lbd0    =xin(2)
          lbd1    =xin(3)
          Tmpsta  =xin(4)
          Tmpstp  =xin(5)
          Tsens   =xin(6)
          IF ( ((Tsenspr>Tmpsta).AND.(Tsens<=Tmpsta)) .OR.
      1   ((gpr==0).AND.(g>0)) ) THEN
              istart = 1
              tsta0  = TIME
              tsta1  = TIME + dtsta1
              tsta2  = TIME + dtsta1 + dtsta2
              tstp   = TIME + 999999
              tfanstp= TIME + 999999
          else if ( (Tsenspr<= Tmpstp.AND.Tsens>Tmpstp)
      1           .OR.(gpr>0.AND.g==0) ) THEN
              istop = 1
              tsta0 = 0
              tsta1 = 0
              tsta2 = 0
              tstp  = TIME
              tfanstp = TIME + dtfstp
              Pcmbstp =Pavgmpr
          end if

          if (tsta0 < 0) then
              Opph=0
              Pcmb = 0
              mff  = 0
              mfa =mfg50*sqrt( MAX(0.0, (Tg2pr-Toutd)/50) )
```

```
            Pel  = 0
        else if ((tsta0<=TIME) .and. (TIME<tsta1)) then
            Opph=1
            Pcmb = 0
            mff  = 0
            mfa  = mfgfanstp
            Pel  = Pelsta
        else if ((tsta1 <= TIME) .and. (TIME < tsta2)) then
            Opph=2
            Pcmb = Pcmbsta
            mff  = Pcmb / Hf
            mfa  = mff*Af*(lbd0+(lbd1-lbd0)*Pcmb/Pmax)
            Pel  = Pelsta
        else if ((tsta2 <= TIME) .and. (TIME < tstp)) then
            Opph=3
            Pcmb = g*Pmax
            mff  = Pcmb / Hf
            mfa  = mff*Af*(lbd0+(lbd1-lbd0)*Pcmb/Pmax)
            Pel  = Pe0 + g*(Pe1-Pe0)
        else if ((tstp <= TIME) .and. (TIME < tfanstp)) then
            Opph=4
            Pcmb = Pcmbstp *exp(-(TIME- tstp)/ tcglow)
            mff  = Pcmb / Hf
            mfa  = mfgfanstp
            Pel  = Pe0 + (Pe1-Pe0)*mfgfanstp/((Pmax/Hf)*Af*(lbd1))
        else if ((tfanstp <= TIME)) then
            Pcmb = Pcmbstp *exp(-(TIME- tstp)/ tcglow)
            mff  = Pcmb / Hf

            mfa  = mfg50*sqrt(MAX(0.0,(Tg2pr-Toutd)/50) )
            Pel  = Pe0
            if (Pcmb >= 0.0001*Pmax) Opph=5
            if (Pcmb <  0.0001*Pmax) Opph=0
        end if
    else if (Bmod==2) then
        Opph=-1
        mff  =xin(1)
        mfa  =xin(2)
        Pel  =xin(3)
        Pcmb =mff*Hf
        if ((Pcmbpr==0) .and. (Pcmb >0)) istart = 1
        if ((Pcmbpr >0) .and. (Pcmb<=0)) istop = 1
    end if

C   In all operation modes   ( Bmod = 1 or 2) :
    if (Pcmb <= 0.1) then
        Pcmb=0
        mff=0
    end if
    if  ((mff == 0) .or. ( mfa == 0 ))  then
        O2dry = 0.21
    else
        lbd = mfa / ( mff*Af )
        O2dry = 0.21*(lbd -1) / lbd
    end if
    mfg = mff  + mfa
    gtmp   = Pcmb / Pmax

    UAgm1   = UAgm10    + gtmp*(UAgm11-UAgm10)
    UAgm2   = UAgm20    + gtmp*(UAgm21-UAgm20)
    UAma    = UAma0     + gtmp*(UAma1 -UAma0 )
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    UAmliq  = UAmlq0     + gtmp*(UAmlq1-UAmlq0)
    UAmm    = UAmm0     + gtmp*(UAmm1 -UAmm0 )

    Tm1 = Tm1pr
    Tm2 = Tm2pr
    Tg2 = Tg2pr

    E = 100
    DO WHILE ( E > 0.001 )
        Tm1a= ( Tm1pr + Tm1) / 2
        Tm2a= ( Tm2pr + Tm2) / 2
        Cpg=1.046661+0.00016844*Tg2-
    1   0.168154*O2dry-0.00054628*Tg2*O2dry
        Tg0 = Ta
        If (mfg/=0) Tg0 = Ta + (Pcmb + Pel )/(mfg*Cpg)
        Tg1=Tg0 + (Tm1-Tg0) *exp(- mfg *Cpg  / UAgm1)
        Tg2=Tg1 + (Tm2-Tg1) *exp(- mfg *Cpg  / UAgm2)
        Tlqo=Tlqi+(Tm2-Tlqi)*exp(- mflq*Cpliq/ UAmliq)
        Pgm1 =  Cpg  *mfg *(Tg0 -Tg1)
        Pgm2 =  Cpg  *mfg *(Tg1 -Tg2)
        Pliq =  Cpliq*mflq*(Tlqo-Tlqi)
        Pamb =  UAma *(Tm1 -Troom)
        Pm1m2=  UAmm *(Tm1 -Tm2)
        Tm1=Tm1pr+DELT *(Pgm1-Pamb-Pm1m2) / mcpm1
        Tm2=Tm2pr+DELT *(Pgm2-Pliq+Pm1m2) / mcpm2
        E=ABS(Tm1a-(Tm1pr+Tm1)/2)

    1    +ABS(Tm2a-(Tm2pr+Tm2)/2)
    end do

    Pg   = Pcmb + Pel -Pgm1-Pgm2
    mf   = Pcmb *DELT/Hf
    mfCO= (istart*mCOsta + istop*mCOstp )/DELT
    1     + Pcmb*(DCO0+g*(DCO1-DCO0))
    mfcum   = mfcumpr + mf
    mCOcum  = mCOcumpr + mfCO*DELT
    if (opph==3) then
        mfcumw=mfcumwpr+mf
        Xcaw = Xcawpr + Pcmb*mf
        Pcaw = Xcaw / mfcumw
    end if
    Nstacum = Nstacumpr + istart

    Xpavg=MIN(0.5, DELT/(5/60))    ! For average Pcmb during last 5 minutes
    Pavgm=Pavgmpr*(1-Xpavg)+Pcmbpr*Xpavg

C    SET OUTPUTS
    OUT(1)= Pcmb
    OUT(2)= Pel
    OUT(3)= Pamb
    OUT(4)= Pliq
    OUT(5)= Pg
    OUT(6)= Tm1
    OUT(7)= Tm2
    OUT(8)= mff
    OUT(9)= mfa
    OUT(10)=mflq
    OUT(11)=Tlqo
    OUT(12)=mfg
    OUT(13)=Tg2
    OUT(14)=Cpg
```

```
      OUT(15)=mfCO
      OUT(16)=Nstacum
      OUT(17)=mfcum
      OUT(18)=mCOcum
      OUT(19)=Pcaw
      OUT(20)=Opph

C     Save values for next call or timestep
      S(IST+ 1)=Pcmb
      S(IST+ 3)=Tm1
      S(IST+ 5)=Tm2
      S(IST+ 7)=Tg2
      S(IST+ 9)=Nstacum
      S(IST+11)=mfcum
      S(IST+13)=mCOcum
      S(IST+15)=Xcaw
      S(IST+17)=Tsens
      S(IST+19)=g
      S(IST+21)=Pavgm
      S(IST+23)=mfcumw

      S(IST+31)=tsta0
      S(IST+32)=tsta1
      S(IST+33)=tsta2
      S(IST+34)=tstp
      S(IST+35)=tfanstp
      S(IST+36)=Pcmbstp

      RETURN 1
        END
```