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Transient CFD simulation of wood log stoves with heat storage devices

Claudia Benesch[1], Martina Blank[1], Robert Scharler[1,2],
Manuel Kössl[3], Ingwald Obernberger[1,2]
[1]BIOS BIOENERGIESYSTEME GmbH, Inffeldgasse 21 b, A-8010 Graz, Austria
Tel.: +43 (0)316 481300 61, Fax: +43 (0)316 481300 4; E-mail: benesch@bios-bioenergy.at
[2]Institute for Process and Particle Engineering, Graz University of Technology,
Inffeldgasse 21 b, A - 8010 Graz, Austria;
[3]RIKA Innovative Ofentechnik GmbH, Müllerviertel 20, A-4563 Micheldorf, Austria

ABSTRACT: Wood log fired stoves increasingly constitute effective heating systems due to new innovative concepts including heat storage devices. These devices accumulate a certain fraction of the heat released in a special storage medium for a certain period of time and release it after opening of discharge channels. The combustion of wood logs in small-scale stoves itself is a highly transient and complex process and the transient character of the operation of wood log stoves becomes even more important, when a heat storage system is included. The operation of a heat storage device is divided into 3 phases: heat-up, heat storage and heat discharge. We developed an innovative methodology based on transient CFD simulations in order to analyse the transient heat-up/heat discharge processes in heat storage devices. Selected results are presented including the heating rate of the storage material during the heat-up, the energy release during the storage and the discharging rate during the discharge phase. The influence of the air-flow in the discharging channels and the flue gas flow in the charging channels as well as material properties on the charging/discharging processes is discussed.
Keywords: alternative energy, biomass, modelling, stove, wood.

1 INTRODUCTION AND GOALS

Wood log fired stoves are not only an attractive eye-catcher creating a warm and comfortable atmosphere in the living room, they constitute also increasingly effective heating systems due to new innovative concepts including heat storage devices. These devices accumulate a certain fraction of the heat released in a special storage medium for a certain period of time (e.g. over night) and release it after opening discharge channels. Typical heat storage concepts either store sensible heat (via their heat accumulating capacity) or both sensible and latent heat (via a phase change). In this publication only heat storage devices of the first kind will be regarded.

While CFD simulations of reactive flow in the combustion chamber are successfully being performed for biomass fixed bed and grate furnaces of all scales ([2][3][4][5][6][7]), only recently CFD models for the combustion of wood logs in small-scale stoves became available due to the high complexity of the transient processes occurring in such devices [8]. However, up to now CFD simulations of wood log fired stoves have been limited to stationary operating conditions, due to the complexity and the high computational demand of transient CFD simulations. For this application, BIOS has developed an innovative CFD model for wood log fired stoves operated in batch mode consisting of an empirical model for wood log combustion and CFD models for the turbulent reactive flow and heat transfer in the stove [8].

However, the combustion of wood logs in small-scale stoves is a highly transient and complex process, as a wood log stove is operated in batch mode with one batch consisting of a starting, a main combustion and a burnout phase. The transient character of the operation of wood log stoves becomes even more important, when a heat storage system is included. In this case, steady-state conditions do not apply, as the operation of a heat storage device is divided into 3 phases: heat-up, heat storage (without charging) and heat discharge. Therefore, for the CFD-based characterisation of wood log stoves with heat storage devices, a transient treatment is necessary.

2 METHODOLOGY

To this end, BIOS has developed a new methodology, which runs in several steps:

Step 1: The wood log stove with integrated heat storage device is simulated with the developed basic (stationary) model. This allows to asses the performance of the stove, as well as a characterisation of the steady state behaviour of the heat storage device (corresponds to the fully charged storage unit).

Step 2: A transient simulation of the system of stove and heat-storage device is performed. Thus, the energy distribution in the stove as well as the storage-device can be investigated during the whole cycle of operation (heat-up, heat storage, discharge). This calculation is computationally extremely demanding.

Step 3: In order to save computational time, a transient simulation of the heat storage device alone is performed. The boundary conditions used for this calculation are obtained from step 2 (mass fluxes and temperatures at the entrance to the heat storage device).

Step 4: A sensitivity analysis of the heat storage device is conducted, based on the CFD-simulation of the heat storage device alone (step 3). In this way, it is possible to optimise the heat storage device, while keeping computational time at a minimum.

2.1 Stove and storage device geometry

The basic concept of the 10 kW wood log stove with heat storage device operated in natural convection mode is shown in Figure 1 and 2. The heat storage device is placed on top of the wood log stove.

The computational domain of the wood log stove starts with the combustion air supply, which is divided into the window air and the primary air (supplied below the grate). The window air enters the combustion chamber at the top of the glass window, where it mixes with the fuel gas released from the wood logs and the bed of embers. In the CFD-simulation the wood logs are represented as volumes, where the wood volatiles are released from an outer layer defined as porous zone. The bed of embers, where char burnout takes place, is also modelled as porous zone.

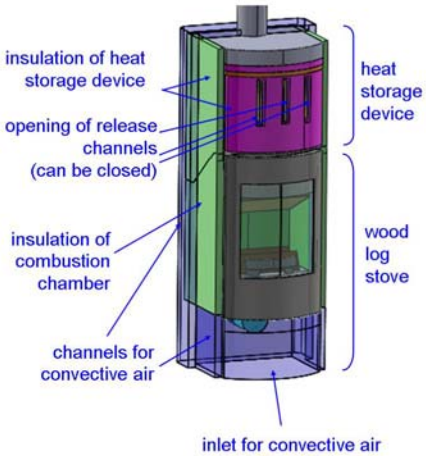

Figure 1: Geometry of the wood log fired stove with integrated heat storage device – 3D view

After leaving the main combustion zone the flue gas enters into one of four vertical charging channels inside the heat storage device. The cross-section at the exit from the charging channels is partly covered by insulation material. The flue gas is re-collected on top of the heat storage device before it escapes via the chimney. Inside the heat storage material there are three skewed discharging channels which open to the front and are connected to the double jacket for convective air at the back of the stove. These channels have to be closed on the front and the back in order to avoid heat release during the heat-up and storage phase and are open during the discharge phase.

The combustion chamber is efficiently insulated by chamotte lining and additional insulation on the outside of the wood log stove, in order to ensure sufficient CO-burnout in the combustion chamber and a sufficiently high flue gas temperature at the entrance to the heat storage device. The heat storage device itself also has to be insulated effectively in order to provide a fast heat-up in the charging phase and moderate heat release during heat storage.

2.2 Operating case and applied models

For the operating case considered, the release of volatiles from the wood logs and the bed of embers is calculated by an in-house developed empirical wood log combustion model [8]. Flow and gas phase combustion simulations are performed using the Realizable k-ε Turbulence Model, the Eddy Dissipation / Finite Rates Kinetics Combustion Model [1] in combination with a global methane 3-step mechanism (CH_4, CO, CO_2, H_2, H_2O and O_2 considered) which has been extended for the wood log combustion model by an additional reaction step and species (volatiles), respectively, and the Discrete Ordinates Radiation Model. The CFD sub-models were validated by lab-scale test cases ([see [3], [7]). The overall CFD model for biomass fixed bed furnaces (in combination with the basic empirical fixed bed combustion model) was validated with test runs for several biomass fixed bed and grate furnaces (see e.g. [7]). The CFD based model for wood log fired stoves, which constitutes an enhancement of the overall model for biomass fixed bed furnaces, was checked by a comparison with measurements during several test runs and with different kinds of stoves [8]. Furthermore, the shell conduction model for heat transport within metal sheets is used.

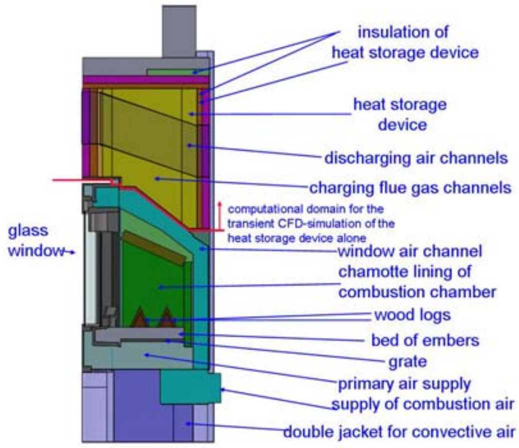

Figure 2: Geometry of the wood log fired stove and the heat storage device – sectional sideview; the computational domain for the simulation of the heat storage device alone is indicated

All CFD simulations were done for a steady-state operating case (Table I) defined based on the test run data with a similar stove and subsequent scaling of the release and heat flux profiles to the new initial fuel mass. This steady state occurs after 63% of the batch time. At this point of operation the heat release to the surroundings is equal to the heat release from the fuel to the stove.

Table I: Operating conditions: fuel composition, calorific values, mass fluxes, total air ratio and oxygen concentration at flue gas outlet

parameter	unit	
water	wt% w.b. ash-free	8.1
C	wt% d.b. ash-free	42.7
H	wt% d.b. ash-free	6.8
O	wt% d.b. ash-free	50.1
N	wt% d.b. ash-free	0.4
gross calorific value (GCV)	MJ/kg d.b.	17.7
net calorific value (NCV)	MJ/kg w.b.	14.7
fuel power related to NCV	kW	10.3
flue gas in combustion chamber - total	kg/h	26.34
flue gas released from fuel	kg/h	2.51
mass flow of air	kg/h	23.83
total air ratio	[ ]	2.03
O_2 conc. at stove outlet, dry	vol% d.b.	10.7

The operating mode of the heat storage device is as follows (24 hour cycle):

- Heating of wood log fired stove in batch mode in order to charge the heat storage device (duration: 5 h, approximately 5 batches)
- Heat storage/standstill (duration: 10 h/over night)
- Discharge of heat storage tank via natural convection (duration: 9 h)

When simulating the heat-up phase based on stationary operating conditions it has to be kept in mind, that the fluctuations of a real batch operation are not taken into account. Furthermore, there is a slight difference between the available heat in the stationary state and the mean available heat over the batch duration, which leads to a slight overestimation of the stored energy during heat-up.

3 RESULTS AND DISCUSSION

The described procedure and models were successfully applied to the study of a wood log fired stove with an integrated heat storage device of the company RIKA Innovative Ofentechnik GmbH, Austria. Selected results are shown and discussed in this work to highlight the advantages of the application of transient CFD simulations to the analysis of the transient heat-up/heat storage and heat discharge process in heat storage devices.

3.1 Results of the stationary simulation of wood log stove and heat storage device

To evaluate the basic concept of the wood log stove with integrated heat storage device, a CFD simulation of the combined wood log stove + storage device system was performed for stationary conditions. Thereby, the air and flue gas flow, the gas phase reactions in the wood log stove and the heat transfer were simulated.

The heat storage device reaches a stationary state (thermal equilibrium state), when its temperature remains constant and no further charging is possible. Thus, the stationary CFD simulation of the wood log stove and the heat storage device constitute the maximum charging state of the heat storage device and yields information on the maximum temperature inside and on the surface of the device and insulation linings, which may be achieved.

The stationary simulation gives no information on the time-dependence of the underlying processes (charging and discharging time, duration until stationary state is reached). Practically, the stationary state of the heat storage device is not reached after 5 h of heat-up. During the stationary simulation the discharging air channels were closed at front- and backside.

Inside the charging channels the flue gas flow concentrates at the rear part of the channels, so that the channels are not evenly flown through (see Figure 3). However, there is a slight recirculation inside the flue gas channels, which increases the residence time of the flue gas within the channels and should contribute to an improved heat exchange.

The stationary CFD simulations showed that the distribution of the flue gas onto the four charging channels is quite even with 28% of the flue gas mass flow passing through the two inner channels and 22% of the flue gas mass flow passing through the two outer channels. This is an important point with regard to an efficient heat exchange between flue gas and charging channel walls.

In the stationary state the temperature distribution in the heat storage device is quite homogeneous with a slight gradient from the center to the isolated boundaries (see Figure 4). The mean material temperature in this state is 373 °C, while the maximum material temperature amounts to 455 °C.

Figure 3: Pathlines of combustion air and flue gas coloured by oxygen concentration [m³ O_2/m³ wet flue gas] – side view

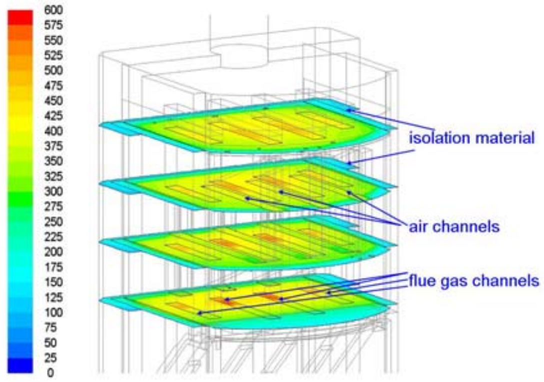

Figure 4: Iso-surfaces of flue gas, air and material temperature in the heat storage device (stationary simulation)

3.2 Results of the transient simulation of wood log stove and heat storage device

In the next step a transient CFD simulation of the combined wood log stove and storage device was performed. This simulation is computationally very demanding, as the whole geometry has to be taken into account and chemical reactions have to be included.

In transient simulations the final state of one phase constitutes the starting state of the next phase i.e. the final charging state corresponds to the starting storage state and the final storage state corresponds to the starting discharging state. Starting from the cold state of the heat storage device, charging, storage and discharging were simulated as a function of time.

For all transient simulations the time step size was chosen very small (< 0.01 s) at the beginning of the charging and the discharging phase. Once the flow field was established the time step size could be increased significantly (up to 20 s) and also during the storage phase, where there is no air or flue gas flow, the time step size could be chosen quite large.

At the end of the heat-up phase the total system stores 9.2 kWh of thermal energy in the storage device with a maximum material temperature of the heat storage device of 422 °C. Additional 6.3 kWh of heat are stored in the wood log stove linings, insulation and metal sheets. The storage device is loaded via the heat exchange with the hot flue gas and the heat transfer from the bottom wall of the heat storage device, with the contribution of the flue gas clearly dominating.

In contrast to the stationary simulation, in the transient simulation there is a pronounced gradient in the temperature distribution of the heat storage device material (see Figure 5), with much higher temperatures in the lower regions of the heat storage device, than in the upper regions. As the hot flue gas enters the heat storage device from below, the heat-up mainly takes place from bottom to top. Due to the rather low thermal conductivity of the material the heat is slowly distributed within the heat storage device, creating large temperature gradients.

Due to the low surface temperatures at the front of the heat storage device (70 – 80 °C), the chosen thermal insulation layers can be considered as sufficient.

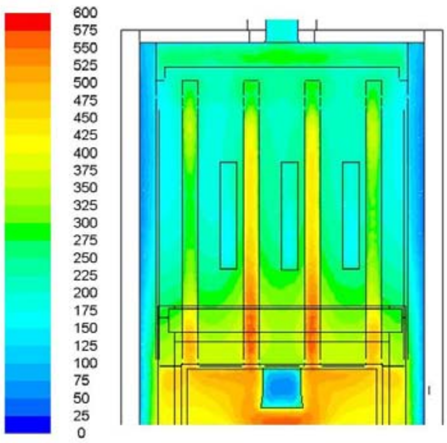

Figure 5: Iso-surfaces of flue gas, air and material temperature in the heat storage device (transient simulation of heat storage device + wood log stove – 3 h after start of heat-up); vertical cross section through the rear part of the flue gas channels

During the storage phase the mean material temperature of the storage device decreases from 283 °C to 112 °C, while the stored heat decreases from 9.2 to 3.1 kWh. Thus, only about a third of the stored heat is available for the discharging phase. This considerable heat release is due to insufficient insulation at the entrance to and exit from the air channels and the flue gas channels as well as insufficient thermal decoupling to the wood log stove beneath. The wood log stove itself looses more than 85% of the stored heat during the standstill phase.

Because of the heat release caused by the metal sheet at the bottom of the heat storage device, during the storage phase, the maximum temperatures inside the storage device shift from the lower regions of the storage device to the upper regions of the storage device and remain there also at the beginning of the discharge phase (see Figure 6).

During the discharge phase the stored energy in the heat storage device decreases from 3.1 kWh to 0.8 kWh. This means, that no total discharge of the stored heat could be accomplished within the chosen length of the discharge phase. It turned out, that only a small fraction of the heat release during the discharging phase is caused by natural convection of air through the discharging channels and the double jacket for convective air. Most of the heat is released by radiation from the surfaces of the storage device, which becomes less efficient at smaller surface temperatures.

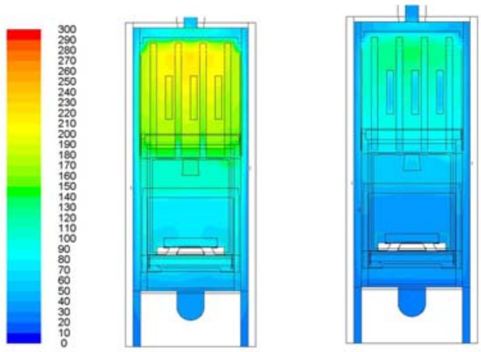

Figure 6: Iso-surfaces of flue gas, air and material temperatures in the wood log stove and the heat storage device (left image: 10 h after start of heat-up/middle of storage phase; right image: 16 h after start of heat-up/1h after start of discharge phase); vertical cross section through the rear part of the flue gas channels

As most of the heat is dissipated via radiation from the surfaces, the storage phase almost continually passes into the discharging phase (see Figure 7).

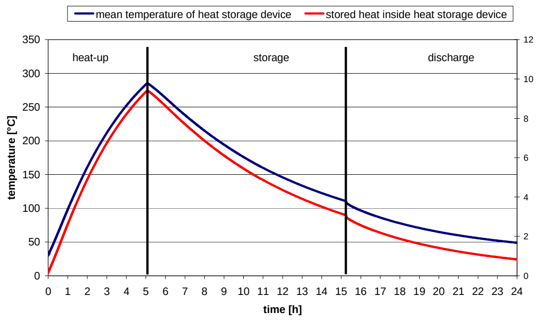

Figure 7: Profile of the mean temperature and the stored heat inside the heat storage device (transient simulation of the total system)

3.3 Results of the transient simulation of the heat storage device alone

Simultaneously to the transient simulation of the wood log stove + heat storage device the computationally less expensive transient simulation of the heat storage device alone was started. The boundary conditions of this simulation were taken from the stationary simulation of the wood log stove + heat storage device system (see Section 3.1). These were (see Table II):

- the flue gas mass fluxes at the entrance to the four flue gas charging channels
- the mean flue gas temperature at the entrance of the four flue gas charging channels
- the wall temperatures at the bottom of the heat storage device

The main difference between the transient simulation of the total system and the storage device alone is that the storage device alone is simulated with these constant boundary conditions, while in the simulation of the total system the temperatures of the flue gas at the entrance to the storage device as well as the surface temperature at the bottom of the storage device are themselves a function of time, which during the heat-up phase asymptotically strive towards their steady state value. During the storage and discharge phase these boundary conditions have been set adiabatic, which turned out to be too optimistic compared to the transient simulation of the total system.

Table II: Boundary conditions for the simulation of the heat storage device alone taken from the stationary CFD simulation of the wood log stove + heat storage device system (Section 3.1)

		Bottom of storage device	Flue gas channel left	Flue gas channel center-left	Flue gas channel center-right	Flue gas channel right
Parameter	unit					
mass flow of flue gas	[g/s]	-	1.58	2.08	2.08	1.57
mean temperature	[°C]	388	512	574	574	511

As the stationary simulation showed that no noticeable flue gas burnout takes place in the heat storage device, the chemical reactions were de-activated for this simulation and only flue gas/air flow as well as heat transfer were simulated.

The transient simulation of the heat storage device alone shows a mean material temperature in the heat storage device of 310 °C and maximum temperature values of 440 °C after 5 h of heat-up. Thus about 10 kWh of heat can be stored inside the heat storage device.

The material temperatures of the storage device in the simulation of the reduced system regarded at the same point of time are a bit higher, than in the total system, the temperature distribution, however, is quite similar qualitatively (see Figure 8).

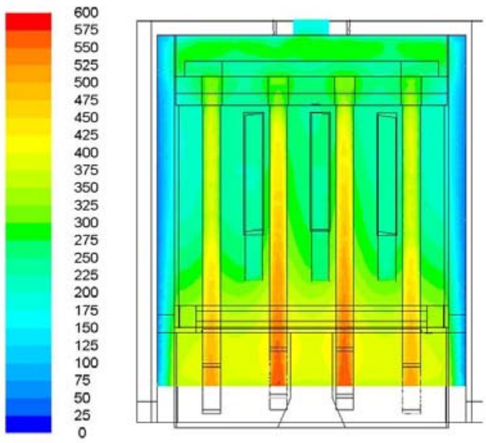

Figure 8: Iso-surfaces of flue gas, air and material temperature in the heat storage device (transient simulation of heat storage device alone – 3 h after start of heat-up); vertical cross section through the rear part of the flue gas channels

When analyzing the results of the transient CFD simulation of the heat storage device alone it has to be kept in mind, that, in practice, the wood log stove and its insulation linings have to be heated up first. By comparison with the transient CFD simulation of the total system a delay of about 1 h occurs compared to the reduced system (amount of heat stored after 5 h of heat-up corresponds to about the results achieved by transient simulation after 6 h).

During the storage phase the stored heat inside the storage material decreases from 10.2 kWh to 4.9 kWh and the mean temperature of the storage material decreases from 310 °C to 161 °C. This heat release is smaller than in the simulation of the total system, due to the adiabatic boundary condition of the metal sheet assumed at the bottom of the storage device. In the simulation of the total system the heat release caused by this metal sheet is considerable.

During the discharging phase the mean temperature of the storage material decreases from 161 °C to 69 °C corresponding to a decrease in stored heat from 4,9 kWh to 1,6 kWh.

3.4 Results of the design study (sensitivity analysis) of the heat storage device alone

As the transient CFD simulation of the total wood log stove + heat storage device is computationally expensive, the design study was done for the reduced heat storage device system alone.

During the design study 4 geometric variants with several changes in the storage device geometry were simulated and also material property variations were analyzed.

Geometric variations (selection):

- removal/enlargement of double jacket for convective air
- reduction of the cross-section of the flue gas exit from the storage device
- steeper inclination of the air channels
- removal of air channels (increase of mass of heat storage material)
- better insulation of the heat storage device towards the metal sheet at the bottom
- better insulation of discharging air channels at the back (towards the double jacket for convective air)

Material property variations:

- increased heat conductivity (2x)
- increased density (2x)
- both increased heat conductivity and density (2x)

The thermal isolation between the heat storage device and the metal sheet at its bottom causes a slower increase in the maximum temperature of the heat storage device. In this case the charging is slower at the beginning of the heat-up phase but becomes more efficient, the longer the heat storage device is charged.

At the end of the charging phase the variant without discharging air channels showed higher maximum material temperatures in the heat storage device, than the variants with discharging air channels. This indicates that the air channels, although they are insulated at the front and back, contribute to a higher heat release during the heat-up phase.

The increased mass of the storage material when removing the discharging air channels leads to a small increase of the stored energy after 5 h of charging compared to the basic variant (see Figure 9). A slightly higher increase of the stored energy is observed with better isolation of the air channels at the back. In general, the stored energy at the end of the charging phase is quite similar between the simulated geometric variants.

During the storage phase the largest heat release occurs for the variant without double jacket for convective air. In this case, the stored heat at the end of the standstill phase amounts to 2.9 kWh. The best heat storage capability is found in the geometric variant without discharging air channels, with 6.7 kWh of stored energy at the end of the standstill phase, about 2 kWh more than in the basic variant.

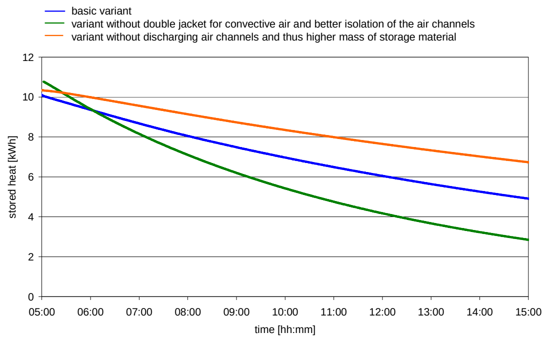

Figure 9: Heat release during the storage phase for different geometric variants

During the discharge phase the geometric variant with a steeper inclination of the air channels shows a larger contribution of convective heat transfer, than in the basic variant, but it is still small compared to heat dissipation via radiation from the storage device surfaces. For the geometric variant without discharging air channels the stored heat decreases from 6.7 kWh to 4.7 kWh i.e. because of the efficient insulation, more heat remains in the storage device at the end of the discharging phase.

The material variation was simulated for the heat-up phase alone. Thereby, a material with increased heat conductivity, increased density and both increased heat conductivity and density compared to the basic material were analyzed.

The increased heat conductivity leads to about 1 kWh more of stored heat at the end of the heat-up phase (see Figure 10). Simultaneously the maximum temperature in the storage material is lower in the variant with increased heat conductivity compared to the basic variant, as the heat inside the storage material is better distributed.

The increase of the storage material density leads to a slower increase of the mean temperature inside the storage material. After 5 h of heat-up the mean temperature in the storage material is 231 °C, which is significantly smaller than in the basic variant (310 °C). As also the surface temperatures of the heat storage device are much smaller when the density is increased, it is to be expected, that this leads to a lower heat release during the storage phase, as the temperature difference between the surfaces of the storage device and the environment becomes smaller. The profile of the maximum temperature looks quite similar for the basic variant and the variant with increased heat conductivity.

When increasing the storage material density the stored heat inside the storage device at the end of the heat-up phase amounts to 14.9 kWh. This is almost a 50% increase compared to the basic variant. Due to this and the expected smaller heat release during the storage phase, the stored energy at the beginning of the discharge phase is expected to be considerably higher.

The CFD simulations of the variant with both increased heat conductivity and increased density showed the combined effects of the two material properties. At the end of the heat-up phase the mean material temperature of the heat storage device (237 °C) is slightly larger compared to the variant with increased density alone (231 °C) but still much smaller than the one of the basic variant (310 °C) and the variant with increased heat conductivity only (337 °C), because of the better distribution of heat inside the storage material when the thermal conductivity is higher. Due to this, also the maximum temperature of the heat storage device decreases compared to the variant with increased density only.

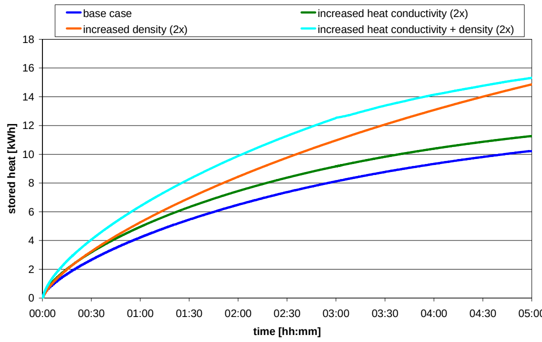

Figure 10: Stored heat during the heat-up phase for different material property variations

At the end of the heat-up phase the variant with increased heat conductivity and density displays the highest value of heat stored inside the storage material (15.3 kWh). However, compared to the variant with increased density only a small increase of 0.4 kWh can be achieved. The higher thermal conductivity of the storage material leads to higher surface temperatures compared to the variant with increased density only. This is expected to lead to a higher heat release during the heat storage phase.

Concluding it has been shown, that both increased thermal conductivity and increased material density lead to an increase of the stored heat at the end of the heat-up phase, where the density turned out to have a much larger effect than the thermal conductivity. The increase of density also has the advantage of much smaller storage material temperatures, which should lead to a smaller heat release during the storage phase. The increased thermal conductivity, on the other hand, bears the risk of a larger discharge during the storage phase, as heat is faster transferred from the material to the surface.

4 SUMMARY AND CONCLUSIONS

With the innovative CFD simulation methodology applied it was possible to derive and discuss the heating rate of a heat storage device coupled to a wood log fired stove during heat-up, heat release during the storage phase and the discharging rate during the discharging phase. Moreover, the influence of the air-flow in the discharging channels and the flue gas flow in the charging channels as well as material properties on the charging/discharging processes have been identified.

The methodology has been applied to the CFD aided development of a wood log fired stove with heat storage device of the Austrian stove manufacturer RIKA Innovative Ofentechnik GmbH. Starting from the stationary CFD analysis of the basic concept of the stove and heat storage device, a transient CFD simulation of the heat storage device + wood log stove system as well as a transient CFD simulation of the heat storage device alone as a basis for a subsequent sensitivity analysis have been performed.

Concluding, the results showed that the stove including the heat storage device geometry can be optimised more effectively by this new and innovative CFD method for the transient simulation of stoves than by trial-and-error test runs. It constitutes a powerful tool for the support of the development of new stove concepts and the evaluation and optimisation of heat storage devices. Moreover, it contributes to a better understanding of the underlying processes and thus to a more efficient system optimization.

Concluding, transient CFD simulations for wood log fired stoves were successfully applied. It could be shown, that despite the complexity of the underlying processes, the methodology is well suited to perform realistic 3D simulations of wood log fired stoves and heat storage devices and hence represents an efficient analysis and design tool. Applying such simulations considerably reduces the effort for test runs and ensures a time-efficient and targeted solution finding.

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6 LOGO SPACE