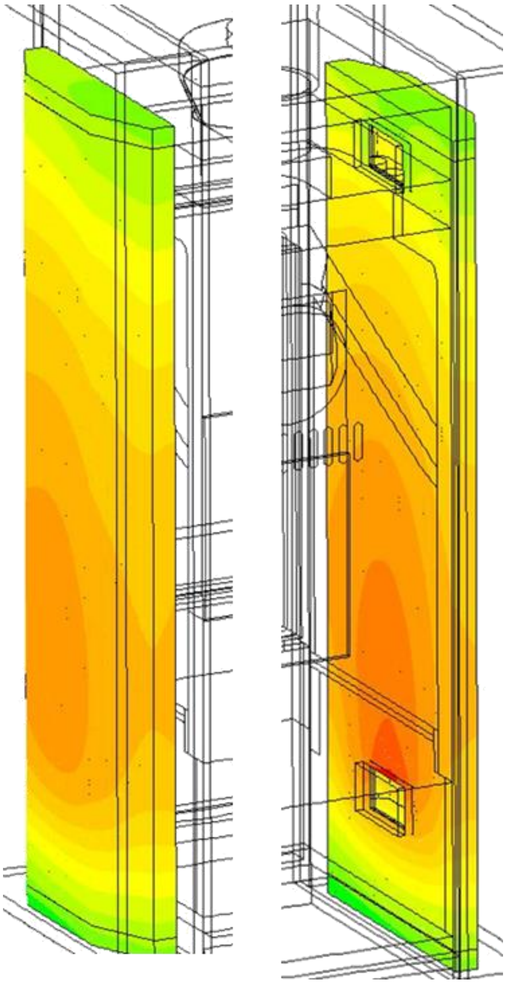
Guidelines for heat storage units based on Phase Change Materials (PCM)



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Report within the scope of the ERA-NET Bioenergy Project “Woodstoves2020” – Development of Next Generation and Clean Wood Stoves

July 2017

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Preface

ERA-NET Bioenergy is a network of national research and development programmes focusing on bioenergy which includes 14 funding organisations from 10 European countries: Austria, Denmark, Finland, France, Germany, Ireland, The Netherlands, Poland, Sweden and the United Kingdom. Its mission is to enhance the quality and cost-effectiveness of European bioenergy research programmes, through coordination and cooperation between EU Member States. The project *Woodstoves2020* (Development of next generation and clean wood stoves) has been supported in the period between August 2014 and July 2017 by ERA-NET Bioenergy under the 7th Joint Call for Research and Development of ERA-NET Bioenergy from 2013.

Today small-scale biomass combustion is one of the most relevant bioenergy applications. Driven by EU-wide and national measures to promote the utilisation of biomass for energy production, the European market for biomass based residential heating systems is expected to substantially increase by about 130% until 2020 (based on 2009). Regarding the installed units stoves show the highest and steadily increasing numbers in Europe. According to market studies performed within the EU FP7 project EU-UltraLowDust (Project No. 268189), in 2020 in Europe a potential for an annual installation of almost 2,200,000 stoves (logwood and pellet stoves) is forecasted.

This additional potential for renewable energy production will of course contribute to a reduction of the EU greenhouse gas emissions. However, it is also well known that among the different residential biomass combustion technologies logwood stoves show the highest CO, OGC and fine particulate matter (PM) emissions.

Against this background, the project *Woodstoves2020* aims at the development of innovative measures and technologies in order to further reduce emissions from wood stoves, to increase their thermal efficiency and to expand their field of application from solely single room heating to central heating. The latter could especially be of relevance for future applications in low energy buildings.

Accordingly, the detailed objectives of the project can be structured as follows.

Objectives related to emission reduction

- Development and implementation of automated control systems for stoves as a feature of new stoves but also as retrofit units for existing models. Automated control systems can help to widely eliminate user induced operation errors and therefore have a huge potential for emission reduction.
- Evaluation and test of new high-temperature catalysts specially adapted to wood stoves for efficient CO, OGC and soot emission reduction. Catalysts should be implemented in new stove concepts as a basis for an ultra-low emission operation which could be comparable to the emission level of automated small-scale boilers.
- Evaluation and test of foam ceramic materials for efficient PM emission reduction.
- Evaluation of the implementation of modern chimney draught regulators.

Objectives related to increasing efficiency and new fields of application

- Development and evaluation of efficient and novel heat storage options for stoves such as the application of PCM (phase change material) with high heat storage potential.

- Investigations regarding efficient heat recovery from stoves (increase of efficiency by the implementation of heat storage units or measures to stabilise the draft or to reduce standing losses).

Objectives related to the implementation and evaluation of the different measures

- Test of the most promising concepts by performing test runs with prototypes.
- Development of design guidelines for stove manufacturers based on the evaluation of the new technologies tested towards a clean stove technology 2020.
- Development of guidelines for the implementation and retrofit of selected measures for old stoves.

With the new technologies developed within the project an emission reduction between 50 and 80% and an increase of the efficiencies in a range above 90% shall be possible. If in future all newly installed wood stoves in Europe would be equipped with these new technologies, a PM emission reduction of 60 - 90% could be achieved.

In order to reach these objectives, a consortium of 4 research organisations and 4 industrial partners from 4 European countries collaborated within Woodstoves2020 (see next page).

This document summarises the outcomes of the investigations regarding the development of heat storing stoves based on Phase Change Materials (PCM) with increased efficiency.

It should support stove manufacturers concerning the optimisation of their products and the development and design of new products with its recommendations which have been worked out based on scientific investigations as well as comprehensive test runs.

Woodstoves2020 project partners

Project coordinator

Technologie- und Förderzentrum	Technology and Support Centre in the Centre of Excellence for Renewable Resources (TFZ) Straubing, Germany

Project partners (R&D)

BIOS	BIOS BIOENERGIESYSTEME GmbH Graz, Austria
RI. SE	RISE Research Institutes of Sweden AB Borås, Sweden
DTU	Technical University of Denmark, Department of Chemical and Biochemical Engineering, Lyngby, Denmark

Industrial partners

RIKA	RIKA Innovative Ofentechnik GmbH Micheldorf, Austria
KW KUTZNER + WEBER	Kutzner + Weber GmbH Maisach, Germany
NIBE	Nibe AB, Markaryd, Sweden
HWAM intelligent heat	HWAM A/S, Hørning, Denmark

Table of contents

1 Introduction and objectives

Today small-scale biomass combustion is one of the most relevant bioenergy applications. Driven by EU-wide and national measures to promote the utilisation of biomass for energy production, the European market for biomass based residential heating systems is expected to substantially increase by about 130% until 2020 (based on 2009). Furthermore, small-scale residential biomass combustion for space heating and warm water production holds a considerable share on the total energy production from biomass (about 50% in 2014 within the EU 28) [1]. Regarding the installed units stoves show the highest and steadily increasing numbers in Europe. However, even modern stoves show clearly lower thermal efficiencies (in the range of 82% under test stand conditions) [2] in comparison to automatically fed and controlled biomass boilers (e.g. pellet boilers). Heat storing stoves (or appliances with integrated heat storage unit) may show significantly increased efficiencies and therefore also contribute to a better economy of stove technologies. Moreover, they contribute to a better climate in the rooms as the energy released to the room can be better distributed over a rather long period in comparison to state-of-the-art wood log stoves.

Innovative compact thermal energy storage technologies are based on the physical principles and properties of phase change materials (PCM) and on thermochemical materials (TCM). With these materials, heat can be stored in a denser form than in e.g. hot water storage tanks.

Data from the literature and comprehensive experimental work as well as from CFD simulations form the basis of this guideline. The guideline aims at supporting manufacturers in the development of heat storing stoves or stoves with heat storage units as add-on options.

1.1 Target group

This guideline provides information primarily for stove developers and manufacturers to use the presented concept for the development of heat storing stoves with increased efficiency. Furthermore, the report should also be of interest to researchers, stove users and policy makers.

2 Definitions and limitations

2.1 Definition of chimney stoves

The present guidelines cover heat storage units for residential chimney stoves. The following features apply to a chimney stove (Figure 1).

- It is a free standing room heater, not walled, and usually with a front window.
- Only a relatively small amount of heat storage is possible due to the low mass of the stove, but heat storage devices could be added to the stove in order to improve the efficiency
- Fuel is charged in a single layer onto the bed of embers (typically logwood).

- Therefore: frequent re-charging is required.
- Heat is released by radiation from the window or from other surfaces and by convection via air ducts and outlets.

Figure 1: Examples of chimney stoves (from left to right: Contura, Rika, HWAM A/S)

2.2 Limitations

Tiled stoves, open fire places, cooking stoves, all stoves with water jackets, pellet stoves and sauna stoves are not covered in this guideline.

Apart from all practical questions concerning heat storage and increasing the efficiency, further technical improvements are also possible, e. g. by a better stove design or by automated control. But such primary and secondary measures are separately presented in other guidelines which have also been prepared during this ERA-NET-project (see [12] and [13]).

3 Basics/Fundamentals of heat storage based on PCM

Heat storages (thermal energy storage) allow to store heat energy in a reversible process and to use the stored energy for heating a house by slow heat release during the times when the stove is not in operation, given that the heat has previously been produced over a typical number of subsequent combustion batches (3 to 6). Regarding heat storage, the following storage methods can be distinguished [3]:

- Sensible heat storage (e.g. water storage tanks)
- Latent heat storage (e.g. based on phase change materials)
- Thermochemical heat storage (e.g. silica gel, metal hydride, zeolite)

Sensible heat storage systems are the most commonly used method for heat storage. In such heat storages the temperature of a storage medium (e.g. hot water tank) increases when heat is supplied and sensible heat is stored. If the storage is cooled again, the temperature decreases and the stored heat is released.

In latent heat storage systems the heat supplied can also be stored as latent heat in addition to sensible heat. If a solid is heated to the melting point and heat is further supplied, the solid starts to melt while the temperature remains constant (isothermal phase conversion). The heat required to change the state (heat of fusion) is called latent heat. Only after the phase transformation has been completed, a further temperature increase of the material and furthermore storage of sensible heat takes place. By cooling the molten material the temperature drops again to the solidification point. When the material is further cooled, the previously molten material is again transferred to the solid state. The latent heat (required for melting) is released again at constant temperature.

Thermochemical heat storages are based on the heat storage by means of chemical reactions. The difference between the enthalpy of the reactants and the reaction products formed during a chemical reaction is called heat of reaction. If heat is released during the chemical reaction (negative reaction enthalpy), this is called an exothermic reaction. If heat (energy) is consumed during the chemical reaction (positive reaction enthalpy), this is called an endothermic reaction.

Chimney stoves currently available on the market with integrated heat storage (storage fireplace ovens) are equipped with a heat storage typically based on soap stone. Since only the sensible heat can be stored with a soap stone, such solutions are usually heavy or voluminous, whereby their residential application is limited. PCMs (Phase Change Materials) enable a more efficient energy recovery from the flue gas as they usually show low melting temperatures, whereby also the latent heat can be stored in addition to the sensible heat. This guideline focuses on heat storage based on PCM due to their innovative approach, compact format and since PCMs have been investigated in detail within this ERANET project.

3.1 Advantages and potentials of heat storage based on PCM

The main advantage of heat storing stoves based on PCM is their significantly increased efficiency as also latent heat can be stored in addition to sensible heat (efficiencies in a range above 90% shall be possible). Moreover, these stoves contribute to a better climate in the rooms as the stored heat released to the room can be better distributed over a rather long period in comparison to state-of-the-art wood stoves. Furthermore, as also the latent heat can be stored in addition to the sensible heat an implementation of the PCM heat storage into the stove in a compact way may be possible. Concluding, heat storage based on PCM can show valuable advantages and potentials:

- increase the thermal efficiency
- also latent heat can be stored
- slow heat release
- higher comfort for customer
- better room climate

3.2 Challenges for heat storage based on PCM

A large number of different materials and material mixtures are basically suitable for heat storage based on PCM (see Figure 2).

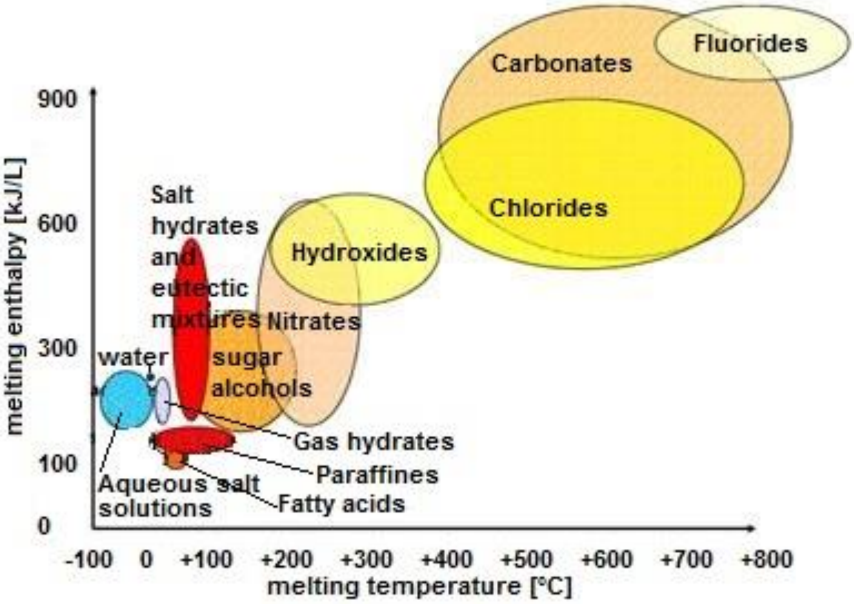

Figure 2: Overview over possible Phase Change Materials (source: [4])

In theory, any material that has a solid-liquid phase transition and a correspondingly high enthalpy of fusion can be used as PCM. However, properties such as heat capacity, density, risk class, availability and price are also relevant for the use of PCMs as heat storage in wood stoves. Moreover, the melting point of the storage material should not be too high as the latent heat storage should be available even during a partial loading of the heat storage. A high density and a high heat capacity of the PCM are important as the heat storage should be compactly integrated into the stove. Concluding, the following criteria are the main challenges for heat storage based on PCM:

- not flammable
- no thermal degradation
- high heat capacity
- high density
- melting point in a suitable range for stoves (150 – 300 °C)
- economically attractive
- not corrosive
- not toxic

3.3 State-of-the-art of heat storage based on PCM

The majority of the commercially available latent heat storage materials are used in the low-temperature range up to a melting point of 150 °C. These materials are already used for various applications and are therefore well developed and tested [5]. Simple and relatively well known low temperature applications of heat storage based on PCM (sodium-acetate-trihydrate) are heat pads and pocket warmers [4]. A form which has long been used industrially is ice water storage in cold-storage systems. In solar heating systems, PCM heat accumulators are used to increase the storage capacity of buffer storage (hot water storage) by inserting a multiplicity of small containers filled with paraffin into the buffer storage, which store latent heat at a temperature of around 60 °C and, if necessary, can return to the water in the buffer storage. However, these PCMs are not suitable for the intended application for heat storage in a logwood stove due to their low melting points and limited thermal stability and have therefore not been further considered.

High-temperature PCM heat storages are used for storing high-temperature heat energy for process steam generation for industrial plants or Concentrating Solar Power (CSP) in solar thermal power plants [6, 7, 8]. Other PCM applications, which are already close to market introduction, include storage of engine exhaust heat from motor vehicles for engine pre-heating during cold start, the integration of PCMs into building materials to reduce heat and cooling demands of buildings as well as the application of PCMs as protection against overheating of sensitive electronic components, data carriers and valuables in case of fire [9].

3.4 Evaluation and selection of a suitable phase change material

As many different types of phase changing materials (PCM) are available on the market, the applicability of these materials for the heat storage in wood stoves has to be evaluated in detail. The following evaluation criteria of phase change materials applied for heat storage units in wood stoves have been considered:

- costs
- thermal degradation behaviour
- heat conductivity
- heat capacity
- density
- toxicity
- flammability
- corrosion potential

A high density and heat capacity of the PCM are important as the heat storage unit should be realised in a dense and compact way. The evaluated PCMs have to be suitable for the application in a heat storage unit (e.g. flue gas heat exchanger) of wood stoves. Accordingly, some basic criteria limit the applicability of these PCMs. These criteria were defined as follows:

- Melting temperature: 150 – 300 °C
    - Should be determined in a way that complete melting can be achieved within a representative number of batches. This can be evaluated by CFD simulations (see chapter 4)
- Degradation temperature: > 600 °C
    - maximum achievable temperature of stove materials can be evaluated by CFD simulations and depends on the isolation applied (see chapter 4)
- The price should be as low as possible in order to be economically competitive

- The material should not be corrosive or toxic under operation conditions

The results of an evaluation performed are summarised in Table 1. As shown there are several PCMs suitable for heat storage in wood stoves. The final selection of the PCM depends on the stove applied.

name	chemical formula	group	melting point	heat of fusion		boiling point	start of degradation	spec. heat capacity		thermal conductivity		density		toxicity / flammability
-	-	-	-	-	-	-	-	solid	liquid	solid	liquid	solid	liquid	-
-	-	-	°C	kJ/kg	kJ/dm³	°C	°C	kJ/(kg*K)	kJ/(kg*K)	W/(m*K)	W/(m*K)	kg/dm³	kg/dm³	-
salts and salt mixtures														
Lithium nitrate	LiNO3	salt	254	360	782	-	>600	1.45-1.88	1.88-2	1.4	0.6	2,1716	1,78	oxidising may cause irritation
eutectic mixture potassium nitrate(54)- sodium nitrate(46)	KNO3-NaNO3	salt mixture	222	100	205	-	600	1.0-1.37	1.37-1.48	0.7	0.5	2,0475	1,95	oxidising cause irritation harmful to health
eutectic mixture potassium nitrate(67)- lithium nitrate (33)	KNO3-LiNO3	salt mixture	133	170	368	-		1.1	1.2			2,166	1,9	oxidising
eutectic mixture lithium nitrate(49)- sodium nitrate (51)	LiNO3-NaNO3	salt mixture	194	265	569	-		1.2-1.39	1.39-1.53		0.5	2,147	1,9	oxidising cause irritation harmful to health
lithium nitrate(55,4)- sodium nitrate(4,5)- potassium chloride(40,1)	LiNO3-NaNO3-KCl	salt mixture	160	266	507							1,905		oxidising cause irritation harmful to health
lithium nitrate(58,1)- potassium chloride(41,9)	LiNO3-KCl	salt mixture	166	272	522							1,918		oxidising may cause irritation
lithium nitrate(47,9)- lithium chloride(1,4)- sodium nitrate(50,7)	LiNO3-LiCl-NaNO3	salt mixture	180	267	530							1,986		oxidising cause irritation harmful to health
LiCl (59.15mol%)- Ca(NO3)2(40,85mol%)	LiCl-Ca(NO3)2	salt mixture	270	167										
NaCl(7,8mol%)- NaOH(85,8mol%)- NaCO3(6,4mol%)	NaCl-NaOH-NaCO3	salt mixture	282	316										
NaCl(8mol%)-NaF(5mol%)- NaNO3(87mol%)	NaCl-NaF-NaNO3	salt mixture	288	224										
Yara Ca(NO3)2(42)-NaNO3(15)- KNO3(43)	Ca(NO3)2-NaNO3-KNO3	salt mixture	131	44			570	1,6	1.45 - 1.55	n.a.	n.a	1,9	1,9	oxidising cause irritation harmful to health

Table 1: Evaluation results of different PCMs (example)

4 Heat storage units for wood stoves based on PCM

Appropriate heat exchangers for the heat transfer from the flue gas to the PCM (loading cycle) and for heat transfer from the PCM to convection air (unloading cycle) are necessary. The heat exchanger should be combined with (or integrated into) the stove concept in a way that a large share of the energy produced is transferred to the PCM.

4.1 Basis concepts and design

Generally, different concepts of heat exchangers are suitable as heat storage units based on PCM. The heat storage unit can be placed e.g. on top of the wood log stove (see Figure 3). Moreover, the heat storage unit (heat exchanger) can be positioned laterally (on one or on both sides) or at the back side of the stove. However, the heat exchanger should be integrated into the stove concept in a way that a large share of the energy produced is transferred to the PCM in order to ensure a high efficiency (up to 90% according to DIN EN 13240).

The release of the stored heat (unloading cycle) can be realised

- Via convection air channels which are opened at the end of operation of the stove. Thus, the stored heat can be distributed even to different rooms (see Figure 4).
- Via slow natural convection over a larger time duration which is of advantage for the comfort of living (see section 4.3)

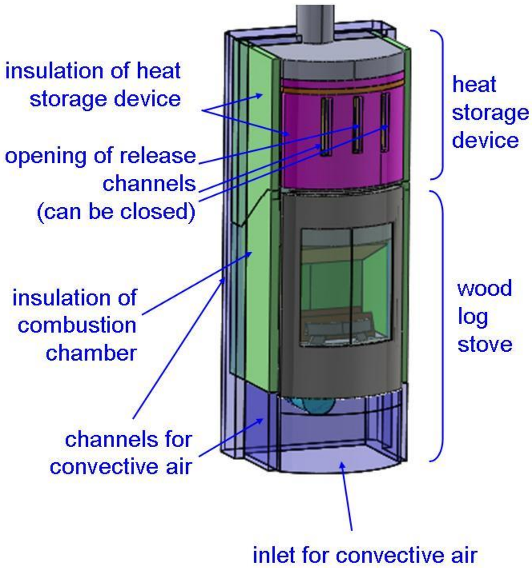

Figure 3: Scheme of the wood log fired stove with integrated heat storage device – 3D view (source: [10])

A good isolation of the PCM heat storage unit is of great relevance:

- It leads to a smaller heat release during the loading phase (share of stored heat can be increased). Generally, 25 to 50 % of the fuel power input should be stored into the PCM heat storage unit.
- The heat storage unit slowly releases the stored heat due to its improved isolation. The heat release from the stove (with integrated heat storage unit) is reduced and gets discharged over a longer period of time (e.g. a whole day) which is of advantage for the comfort of living.

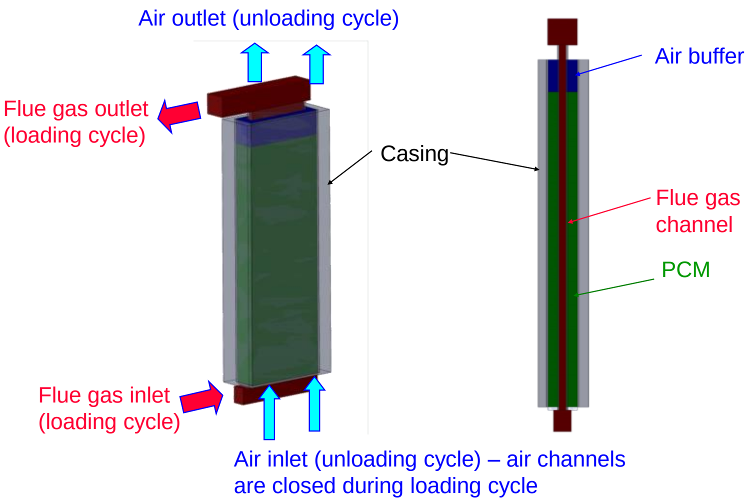

Figure 4: Scheme of a PCM heat exchanger concept with convective air channels (source: BIOS)

The increase of efficiency can be further enhanced by new automatically operating components for air and flue gas control (including complete closure of flaps after shutdown). Beyond the increased efficiency due to a PCM heat storage unit this can further reduce standing losses, which may have a significant impact on the annual system efficiency. As higher efficiencies lead to lower fuel consumption, a strong argument is also provided for users to switch from old to new stove technologies with integrated heat storage units.

The development of a PCM heat storage device can be accompanied and supported by CFD simulations in order to evaluate the performance of the heat storage device. By applying CFD simulations the stove including the heat storage geometry can be optimised more effectively than by trial-and-error test runs.

4.2 CFD-aided design of heat storage units

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 [11]. 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 every 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 release (discharge).

Therefore, BIOS has developed an innovative CFD simulation methodology including a transient simulation of the system [10]. Thus, it is possible to derive and discuss the thermal behaviour of a heat storage device coupled to a wood log fired stove during the heat-up and discharge 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 can be evaluated.

In Figure 5 the surface temperatures of a PCM heat storage unit (similar to Figure 4), laterally coupled to a wood log fired stove (on both sides), are depicted as an example.

The maximum temperature of the PCM can be up to 477 °C for the specific stove investigated and should be significantly lower than the degradation temperature of the selected PCM. The minimum temperature of the PCM is in the steady state 263 °C and it should be above the melting temperature of the selected PCM.

By these innovative CFD methods wood stoves with integrated heat storage units can be optimised more effectively than by trial-and-error test runs. They constitute a powerful tool for the support of the development of new stove concepts and the evaluation and optimisation of heat storage units. Moreover, it contributes to a better understanding of the underlying processes and thus to a more efficient system optimization. The application of such simulations considerably reduces the effort for test runs and ensures a time-efficient and targeted solution finding.

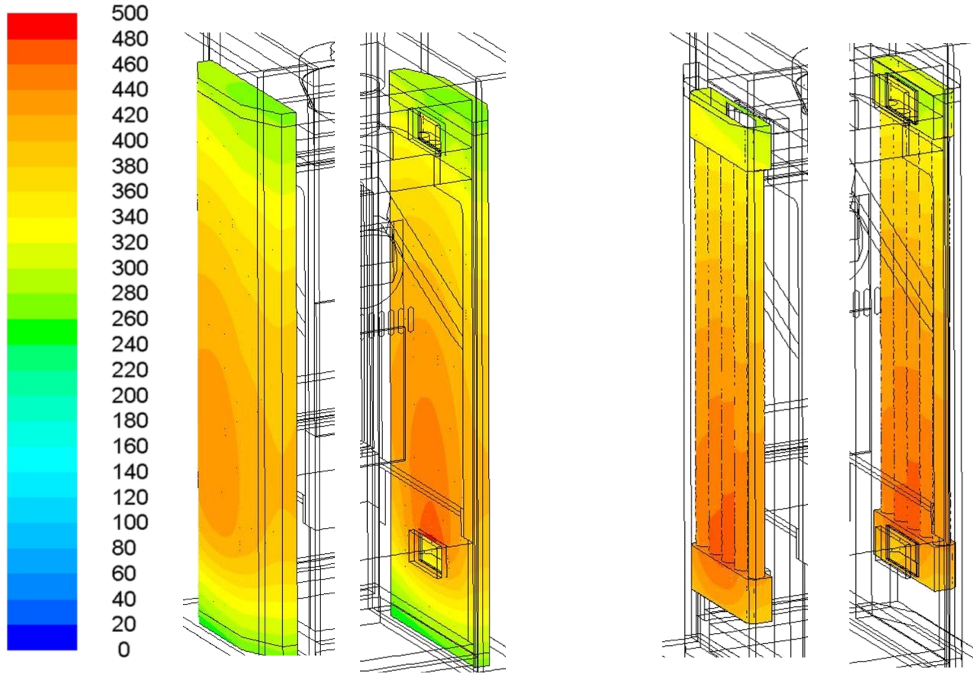

Figure 5: Iso-surfaces of material temperature [°C] in the heat storage unit (steady state after complete charging); 3D view from the left and right side hand of the air channels (source: BIOS)

4.3 Typical operation procedure

The PCM heat storage unit is loaded during the normal operation of the stove. The hot flue gas passes through the PCM heat storage (heat exchanger), sensible heat is transferred to the PCM and the PCM temperature increases continuously. As soon as the PCM starts to melt, also the latent heat can be stored in addition to the sensible heat. Figure 6 shows the energy balance of a typical loading cycle of a wood stove with integrated heat storage unit based on PCM (6 batches at nominal load including the ignition batch):

- Up to 50% of the total fuel power input can be stored in the stove and the PCM heat storage unit, which represents a very attractive value.
- The flue gas losses are low due to the efficient heat storage of the PCM – an efficiency of 90% (according to EN 13240) can be reached for the entire loading cycle

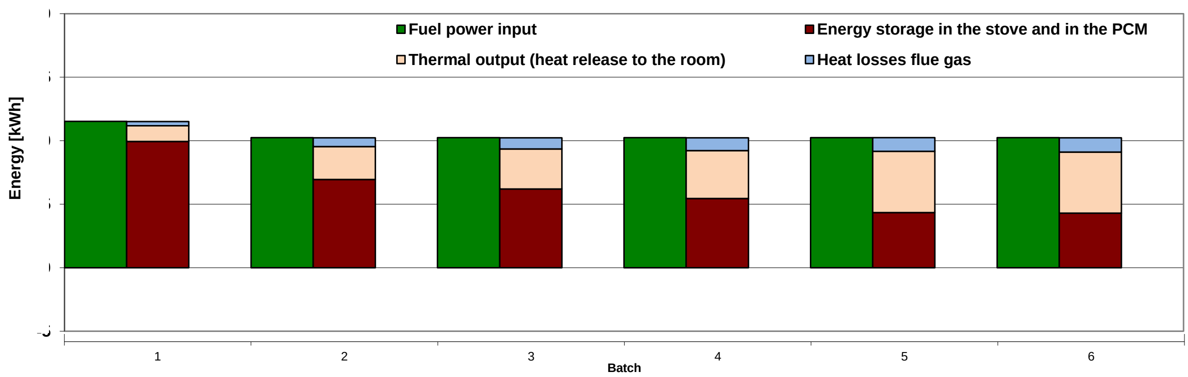

Figure 6: Energy balance of the loading cycle of a wood stove with integrated heat storage unit based on PCM (source: BIOS)

Figure 7 shows a typical unloading cycle (natural convection only) of a wood stove with integrated heat storage unit based on PCM. The air flaps of the stove have been closed at the end of the stove operation (6 batches including ignition batch). This is of relevance in order to reduce standing losses. During the unloading cycle the stove cools down rather quickly. On the contrary, the PCM heat exchanger slowly releases the stored heat due to its improved isolation. After 9 h (duration of the night) up to 20 % of the stored energy in total are still available from the stove and the PCM heat exchanger. The heat release from the stove is reduced and gets discharged over a longer period of time which is of advantage for the comfort of living. By controlling the convective air flow through the heat storage unit the period of heat release can be influenced.

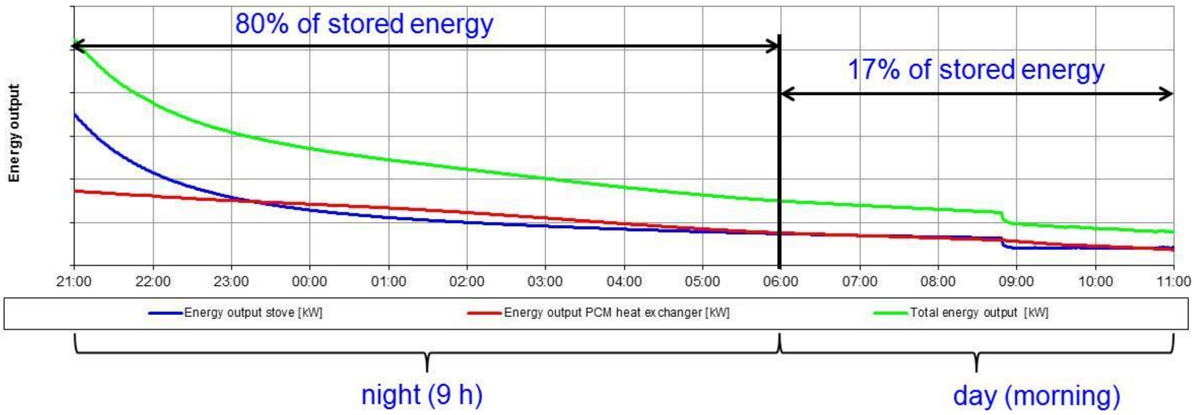

Figure 7: Unloading cycle of a wood stove with integrated heat storage unit based on PCM by natural convection (source: BIOS)

4.4 Development status and market introduction

Based on a new stove concept of RIKA a design for an integrated heat storage system based on PCM has been developed. The development of the stove with integrated PCM heat exchanger has been accompanied and supported by CFD simulations of BIOS in order to evaluate and pre-optimise the new technology. The new wood stove with integrated PCM heat exchanger has been constructed by RIKA and two first prototypes have been erected and comprehensively tested (see Figure 8). The market introduction of the new heat storage technology is expected for 2018.

Figure 8: Picture of the new stove technology with integrated heat storage unit based on PCM (the new stove concept is protected by a patent) (source: RIKA)

5 Acknowledgement

This project was funded within the ERA-NET Bioenergy programme "Small-scale heat and power production from solid biomass". The project consortium gratefully acknowledges the financial support for carrying out the project provided by:

klima+ energie fonds	Klima- und Energiefonds, Austria
FNR Fachagentur Nachwachsende Rohstoffe e.V. / Gefördert durch: Bundesministerium für Ernährung und Landwirtschaft aufgrund eines Beschlusses des Deutschen Bundestages	Fachagentur Nachwachsende Rohstoffe e.V. Bundesministerium für Ernährung und Landwirtschaft, Germany
Energimyndigheten	Swedish Energy Agency

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13. Mandl C., Obernberger I., Hartmann H., Mack R., Schuessler I., Illerup J, 2017: Guidelines for automated control systems for stoves. Report within the scope of the ERA-NET Bioenergy Project "WoodStoves2020", July 2017 www.tfz.bayern.de/mam/cms08/en/dateien/stoves2020-guidelines_automated_control_systems.pdf

7 Useful sources for further information

IEA Solar Heating & Cooling Programme: Website: http://www.iea-shc.org/

IEA Task42 - Compact Thermal Energy Storage: Website: http://task42.iea-shc.org/