Title: Topology and parameter optimization of PCM-based thermal energy storage for 4th generation thermal networks

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Problem statement

The rise in greenhouse gas emissions has led to an increased awareness of energy efficiency of systems and the use of renewable energy sources. To cope with these new trends, new technologies need to be developed to tackle the challenges both at the electrical and at the thermal side.
According to the IEA more than 50% of the final energy consumption today is used for the production of heat. About three quarters of the energy used for heat production is provided by fossil fuels. The remainder is provided by renewable energy sources. However, only a small part comes from more sustainable renewables as bioenergy, solar thermal energy and geothermal energy. Nevertheless, renewable energy use for heat production continues to grow slowly. Heat and cold storage devices may support the development of renewable technologies. As they can decouple the availability of the renewable heat by storing excess heat, they are expected to and facilitate an increased use of renewable heat.
In the present energy context, where classical systems are combined with intermittent renewables to ensure the required supply and demand balance, the following challenges are encountered: 1) the installed power capacity of renewables needs to be supported to a large extent by classical back-up systems leading to large investment costs and enhanced connections in the electrical grid, 2) classical systems often work at partial load and need to cope with fluctuations in time, leading to lower efficiencies both from an energetic and a cost perspective. These challenges can at least to some extent be countered by increased thermal storage capacity. Indeed, in the particular situation of thermal storage the optimal use of solar energy, geothermal energy, cogeneration installations and waste heat recovery are applications that may strongly benefit from cost-effective and efficient heat storage. Solar heat has an intermittent character and is not always available at the time it is needed. In order to make optimal use of the available heat, heat storage devices can be applied in order to provide a better match between supply and demand. Also the share of cogeneration increased strongly in recent years. Very high efficiencies can be reached by producing electricity and heat simultaneously, therefore offering a high primary energy saving. However, the demand for electricity and heat do not always coincide. This problem can be overcome by introducing heat storage devices. Waste heat from incineration plants is present in abundance at different temperatures. This waste heat can be used efficiently by creating a match between demand and availability through the use of thermal energy storages. Likewise, in thermal networks, where balancing demands can be tackled on a local scale, improved thermal storage devices, could greatly contribute to efficient and cost-effective installations.
Currently used thermal energy storage devices mostly consist of water buffers. Their low energy density limits the amount of energy that can be stored in a given volume. Either large temperature changes or large volumes are needed in case a lot of heat needs to be stored. Limiting the temperature change to 10°C results in an energy density of the water storage tank of 42 MJ/m3. In

contrast to water buffers, Phase Change Materials (PCMs) store energy as latent heat (the change of the physical state of a material like melting solid material into the liquid state) and have the advantage of having a high energy density. Different kinds of PCMs exist with energy densities ranging from 130 MJ/m3 to 400 MJ/m3. Because of their high energy density they hold the promise of creating compact and cost-effective storage tanks. However, at present the low thermal conductivity of typical PCMs limits their performance as it forms a barrier to achieving rapid charge and discharge curves. Therefore improved PCM storage concepts will be investigated in this PhD research

Objectives of the research

The overall aim of this research is to push PCM storage vessel designs towards their limits by improving present designs and by exploring new concepts. Because of the low heat conductivity of PCMs, highly conductive (e.g. metal) structures and convection by the liquid will be employed to improve charge and discharge characteristics of the storage vessel. The main research question is:

> *How do PCM storage vessels need to be designed, taking both cost and production techniques and limitations into account to ensure their optimal functionality?*

Together with this research question, answers will be sought to which design is superior from an energetic and economic perspective for a given application, to what degree control strategies can enhance the performance, and in which systems PCM based storage vessels outperform alternative options. Along this research line, attention will also be paid to the possibilities PCMs might offer in other components of thermal networks (e.g. heat exchangers, pipes, …).

In order to achieve this global aim, the following items need to be tackled:

- To investigate optimal designs and controls, a clear definition is needed for 'optimal functionality'. Therefore Key Performance Indicators (KPIs) will be defined to evaluate the performance of the systems. Different aspects need to be investigated: an optimal storage vessel design needs to meet requirements in fast charging and discharging and related operational cost, a constant power delivery and/or a high storage density or related low investment cost.
- Develop a physics based model that captures the basic features of today's existing concepts as encapsulated PCM and finned heat PCM storage vessels. First experience with the optimality criteria and governing sensitivities will be gained using parameter optimization. Thus, performance improvement of existing system designs is envisaged.
- PCM storage vessels can be pushed even further by allowing the development of new topologies. In contrast to a parameter optimization which starts from a well-defined configuration, topology optimization allows finding totally new designs. The minimisation of a cost function will determine the material distribution in a predefined domain. Today's topology optimization methods including phase change is still in its infancy. Starting from the state-of-the-art, a topology optimization procedure will be developed for PCM-metal structures around water tubes.
- The developed optimization procedure will be extended for its use with the encapsulated PCM concept. The PCM particles can be kept fixed. In between these particles metal structures can be created which ensure an optimal flow pattern of the heat conducting fluid. A further extension to multi-material topology optimization will be envisaged which will provide more freedom for new designs.