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Optimal design of heat store filled with solid material

PhD THESES

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1. Background, objectives

Utilisation of forces of nature is as old effort as the history of humanity. If these resources are not available continuously in sufficient quantities, than we have to solve the storage of them. Such a way is collection and storage of the energy of the Sun to provide the heat and electric power requirement for the whole year.

The storage of the heat is possible. The construction of the thermal energy store is very expensive, heat-loss occurs during the heat storage (it means cost as well). The collected heat as a whole cannot be charged into the heat store, the whole stored heat cannot be discharged from the heat store, these are losses (costs) as well. Above these the charge and discharge of the thermal energy store (operation) has energy demand (cost).

For these reasons, the main condition of the practical implementation of industrial-scale heat storage is designing the most economical construction in terms of cost, i.e. optimal one.

Already there are short-term (temporary) heat storages for storage aims at low temperature, for demands of warm water and heating in family houses, and there are heat storages for storage aims at high temperature in thermal power plants. There are also seasonal heat stores for storage aims at low temperature, for warm water and heating demands of a smaller village.

Such seasonal heat-stores (of high temperature and large size) have not yet been built which are suitable for fulfilment of demands of producing of warm water, heating and heat of thermal power plants.

The subject of the thesis is elaboration of calculation method of a new heat storage system with optimization aim and its presentation through application in examples.

2. Evaluation methods

This dissertation shows optimal design of a sensible heat store of new construction, filled with solid heat storage material.
The planned heat store has cascade system formed a spiral flow-path layout. This is a conceptual model, worked out for case of pipe-channelled construction and for case of packed bed with balls.
The aim of the special layout is to realize better overall efficiency than regular sensible heat stores have. By the new construction higher overall efficiency is expected by long flow-way, powerful thermal stratification and spiral flow-path layout which can ensure lower heat loss.
For the mathematical description of the planned system I have adapted one of the discretisation methods developed for solution of differential equations of the heat transport in the heat store. I have worked out a calculation method to simulate the charge and discharge of the heat store, to calculate the overall efficiency using the results of the simulations. The calculation of the overall efficiency takes into account the dischargeable heat quantity without heat-loss, the heat-loss into the environment through the boundary surfaces and the heat-equivalent quantity of the transport work demand as well.
The geometric sizes and operating parameters of the thermal energy store with the best overall efficiency are calculated by application of Genetic Algorithm (GA).
The dissertation shows the application of the simulation and optimization method of the new heat storage system for two cases: *pipe-channelled* construction with *gas and liquid* heat transport medium, and *packed bed* construction with balls with *gas* heat transport medium.

3. New results, theses

I.

I have developed a mathematical model for the calculation of the charge and discharge of a new sensible heat store construction (pipe-channelled thermal energy store) filled with solid heat storage material, with triangular pitch of cylindrical pipe-channels.

a. I have worked out differential equations of the heat transport in the pipe-channelled heat store (two-phase, general, one-dimensional model) using the known differential equations of the heat transport in heat store filled with particles.
b. I have developed simulation model to calculate the spatial temperature distributions of the heat storage material and of the heat transport medium using discretisation of the differential equations of the heat transport in the heat store.
c. I have worked out a calculation method to calculate optimal geometry and operational parameters of the thermal energy store with the best overall efficiency using genetic optimization algorithm (GA) based on the simulation model which calculates the spatial temperature distributions of the heat storage material and the heat transport medium.

II.

I have proved that a thermal energy store of long flow-path is more preferable – because of its powerful thermal stratification – than a short flow-path thermal energy store which has equal mass of solid heat storage material as the long flow-path one, mentioned before. The reasons of it are the following:

a. the great part of the solid heat storage material is being heated up close to the inlet temperature of the heat transport medium, until the end of the charge period,
b. the outlet temperature of the heat transport medium is close to the beginning (low) temperature of the heat storage material in the great part of the charge period, so it has great heat transport capability lasting long,
c. the great part of the solid heat storage material is being cooled down close to the inlet temperature of the heat transport medium until the end of the discharge period,
d. the outlet temperature of the heat transport medium is close to the beginning (high) temperature of the heat storage material, in the great part of the discharge period, so the high temperature level of it is more valuable,

e. it is easier to distribute uniformly the stream of the heat transport medium along the smaller flowing cross-section area of the long flow-path thermal energy store than along the larger flowing cross-section area of the short flow-path thermal energy store.

III.

I have worked out the following solutions to eliminate the disadvantageous properties of the sensible heat store of small flowing cross-section area, long flow-path and great outer specific surface area:

a. In order to reduce the transport power demand of the heat transport medium, I have divided the long flow-path thermal energy store into sections (called ducts) and formed cascade system from them. I have proved that the transport power demand of the heat transport medium will be decreased, if the heat transport medium is flowing through only those ducts where the thermocline zone is going through (i. e. knocking-off those sections from the flow-path of the heat transport medium in which the temperature is in steady-state).

b. In order to reduce the heat-loss – due to the greater outer specific surface area – I have planned a heat store of regular hexagonal prism with outer geometry of $H/S_t \approx 1$ ratio and cascade system of the ducts formed a spiral flow-path layout.

   - The heat transport medium flows from the centre to the outer side of the heat store following the spiral flow-path layout during the charge period. It makes thermal stratification with descending temperature in the flow-direction and radial direction as well. Therefore, the temperature of the outer surface of the heat store is low until the charge up of the outer ring of the ducts, so the heat loss is small during this period of time.
   - During the discharge period (opposite flow-direction to the charge) the temperature of the outer surface of the heat store is low after the discharge of the outer ring of the ducts, so the heat loss is small during this period of time.
   - When the temperature of the outer ring of the ducts of the heat store is low, then the part of the charging and discharging time increases with increase of the number of ducts.

IV.

I have calculated the optimal values of the design variables *for two cases* according to the overall heat efficiency: with *gas and liquid* heat transport medium in case of *pipe-channelled heat store,* with *gas* heat transport medium in case of *packed bed heat store with ceramic balls*. In both cases the heat-flow was of 2 MW steady-state during 63 days of charge and 58 days of discharge. The calculated results are the following:

a. Significantly higher overall efficiency can be reached in case of the multi-duct, long flow-path thermal energy store with cascade system of the ducts formed a spiral flow-path layout than in case of the one-duct type, short flow-path thermal energy store which has equal mass of solid heat storage material as the long flow-path one, mentioned before.
b. The pipe-channelled heat store has higher overall efficiency – because of its lower pressure drop – than the heat store filled with ceramic balls.
c. In case of pipe-channelled thermal energy store the higher overall efficiency can be reached by using small inside wall thickness and much lower flow velocity than the economic flow velocity in pipelines. The powerful thermal stratification requires large number of pipe-channels and small pipe-channel diameter. In case of gas heat transport medium at greater number of ducts the optimal pipe-channel diameter is larger, because of the increasing transport work demand of the heat transport medium.
d. In case of liquid heat transport medium the overall efficiency of the pipe-channelled heat store can be higher than in case of gas heat transport medium. But the heat store with liquid heat transport medium is more dangerous than the heat store with gas heat transport medium. Applicability of the liquid heat transport medium is limited by its heat stability. In terms of operational safety the best solution is the multi-duct, pipe-channelled heat store with approximately atmospheric air heat transport medium, applicability of it is not limited by its heat stability.
e. The sensitivity tests shows that the slight change of the value of the design variables at their optimum cause minimal change of the overall efficiency. This fact provides derogation from the calculated optimum.
f. The worked-out simulation and optimum-searching model can be used effectively to calculate the optimal number of ducts, geometric dimensions and operating parameters.

4. Publications

List of own publications and conference presentations on the subject of the dissertation:

1. Borbély, T.: *Optimal design of high-temperature thermal energy store filled with ceramic balls*, Hungarian Journal of Industrial Chemistry Veszprém, Vol. 40 (2), (2012), pp: 93-99.

2. Borbély, T.: *Optimal design of seasonal pipe-channelled thermal energy store with liquid heat transport medium*, Annals of the Oradea University, Fascicle of Management and Technological Engineering, Volume XXII (XII) Issue 3, (2013), pp: 9-14.

3. Borbély, T.: *Optimal design of seasonal pipe-channelled thermal energy store with gas heat transport medium*, Acta Tehnica Corviniensis – Bulletin of Engineering, Tome VII, Fascicule 1., (2014), pp: 19-26.

4. Timár, I., Horváth, P., Borbély, T.: *Optimierung von profilierten Sandwichbalken*, Stahlbau 72 (2), (2003), pp: 109-113.

5. Timár, I., Horváth, P., Borbély, T.: *Optimization of framework construction*, Strojírenska Technologie 8 (1), (2003), pp: 9-12.

6. Timár, I., Horváth, P., Borbély, T.: *Optimization of cylindrical sandwich constructions*, Publ. Univ. of Miskolc, Series G. Mechanical Engineering Vol. 48. (1999), pp: 175-184.

7. Timár, I., Borbély, T.: *Optimization of insulated pipelines*, Publ. Univ. of Miskolc, Series G. Mechanical Engineering Vol. 47. (1997), pp: 253-258.

8. Timár, I., Horváth, P., Borbély, T.: *Profilos szendvicstartók optimális méretezése*, Gép 50 (1) (1999), pp: 35-40.

9. Timár, I., Horváth, P., Borbély, T.: *Optimization of a welded I-section frame with size limitation*, In: Jármai&Farkas (eds): Metal Sructures Design, fabrication Economy, Rotterdam, Millpress (2003), pp: 183-188.

10. Timár, I., Horváth, P., Borbély, T.: *Optimization of sandwich constructions*, MicroCAD'99 International Computer Science Conference, Miskolc, 1999. február 24-25. Section K, pp: 145-149.

11. Timár, I., Borbély, T., Horváth, P.: *Hengeres szendvicshéj optimálása*, Erdélyi

Magyar Műszaki Tudományos Társaság, VIII. Országos Gépésztalálkozó, Marosvásárhely, 2000. április 7-9., pp: 63-66.

12. Timár, I., Borbély, T., Horváth, P.: *Keretszerkezet optimálása*, Erdélyi Magyar Műszaki Tudományos Társaság, VII. Országos Gépésztalálkozó, Félixfürdő, 1999. április 23-25., pp: 86-89.
13. Timár, I., Borbély, T.: *Rétegezett szerkezetek optimálása*, Erdélyi Magyar Műszaki Tudományos Társaság, VI. Országos Gépésztalálkozó, Hargitafürdő, 1998. április 24-26., pp: 168-172.
14. Timár, I., Borbély, T.: *Költségmegtakarítás optimális méretezéssel*, Erdélyi Magyar Műszaki Tudományos Társaság, V. Országos Gépésztalálkozó, Kolozsvár, 1997. május 23-25., pp: 48-48.
15. Timár, I., Borbély, T.: *Rétegezett tartók költségbecslése és optimálása*, MicroCAD'97 International Computer Science Conference, Miskolc, 1997. február 26-27., pp: 11-17.
16. Timár, I., Bencs, G., Borbély, T., Kulcsár, T., Veres, G.: *Szerkezetek előzetes költségbecslése. Windows alkalmazás konstrukciók előzetes költségbecslésére*, Erdélyi Magyar Műszaki Tudományos Társaság, IV. Országos Gépésztalálkozó, Szováta, 1996. április 12-14., pp: 29-30.
17. Timár, I., Bencs, G., Borbély, T., Kulcsár, T., Veres, G.: *Konstrukciók előzetes költségbecslése*, MicroCAD'96 International Computer Science Conference, Miskolc, 1996. február 29., pp: 31-34.

List of own publications and conference presentations on other science subjects:

18. Balázsi, Cs., Timár I., Verdes S., Bálint, A., Horváth, P., Borbély, T., Lisztes, I.: *Preparation and examination of nanostructured steel powders*, ANNALS of the ORADEA UNIVERSITY, Fascicle of Management and Technological Engineering, Volume IX (XIX), NR1, (2010), p: 3.10.
19. Hanák, L., Szánya, T., Marton, Gy., Pencz, I., Borbély, T., Nagy, K., Kiss, Cs.: *Detoxification of cyanide-containing pharmaceutical wastes by hydrolisys at high temperature*, Conference proceedings Hungarian Journal of Industrial Chemistry Vol. 1. (1999), pp: 18-20.

20. Timár, I., Horváth, P., Lisztes, I., Borbély, T: *Nanoszerkezetű acél kutatási eredményei*, Erdélyi Magyar Műszaki Tudományos Társaság, XIX. Országos Gépésztalálkozó, Csíksomlyó, 2011. április 28 – május 1., pp: 368-371.

21. Ködmön, I., Timár, I., Lisztes, I., Borbély, T: *Speciális gyártástechnológia kifejlesztése gipsz öntőformák készítésére*, Erdélyi Magyar Műszaki Tudományos Társaság, XIX. Országos Gépésztalálkozó, Csíksomlyó, 2011. április 28 – május 1., pp: 216-219.

22. Timár, I., Lisztes, I., Borbély, T: *A DFM-módszer alkalmazása a terméktervezésben*, Erdélyi Magyar Műszaki Tudományos Társaság, XVIII. Országos Gépésztalálkozó, Nagybánya, 2010. április 22-25., pp: 444-447.

23. Ködmön, I., Timár, I., Handa, L., Borbély, T: *Változtatható geometriájú gipszmagok modellezése és új gyártástechnológiájának kifejlesztése*, Erdélyi Magyar Műszaki Tudományos Társaság, XVIII. Országos Gépésztalálkozó, Nagybánya, 2010. április 22-25., pp: 241-244.