

Dynamic Thermal Storage – Physical Design and Systems Integration

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ABSTRACT: The article describes a concept of Dynamic Thermal Storage (DTS) characterised by the ability to switch rapidly between heating/cooling and charging. The DTS is part of an integrated system serving a building, where the temperature drop required for transport of heat is used also for thermal storage. Charging is optimised based on weather forecasts (obtained via Internet), in effect turning natural variation in outdoor temperature into a renewable energy source. A DTS is built like a well, some 3 – 4 m deep, lined with polymer sheet and filled with fired, expanded clay spheres. These carry weight and allow parking or lawns/greenery atop, and stabilises the storage. The DTS operates as a two-phase system similar to chemical chromatographic analysis, with warm and cold zones separated by stagnant water some 0.6 – 0.8 m thick.

The filling is ordinary, lightweight construction material (about €40/m³) filled with water, with a specific heat of 3000 kJ/m³. Maximum effect is 0.3 kW/°C m². Cross sections of 2 – 4 m² and volumes of 5 – 10 m³ fit single homes when optimised over 48 hour time spans. The concept appears economically promising particularly in areas with low installation costs and with large differences in day/night temperature, to give substantially reduced consumption of electric power for air conditioning. Heat pumps may be avoided where/when night-temperatures go below about 17 °C.

Keywords: Energy, dynamic, thermal, storage, system, buildings, cooling, heating

1. INTRODUCTION

World energy consumption has grown exponentially at some 2.3 % annually for more than a hundred years (Grübler et al, 1999), doubling every 30 years or for each

generation. Some 85 % of this is based in fossil fuels. We now face, simultaneously, a realisation that supply may no longer keep up with demand, serious national concern over security of supplies in many countries, and, equally, concern over environmental impact.

At the time of writing oil is topping \$70/barrel, and a discussion of “Peak-oil” has started in earnest. We may expect oil and gas, in particular, to pass from a buyer's to a seller's market, creating a quite new commercial situation for alternative energy supplies.

Large amounts of energy are presently used to maintain suitable indoor conditions; figures of some 35-40 % of total energy use are commonly cited. This means opportunities for extensive improvement by achieving and maintaining suitable conditions while using much less energy. This “Not-Used-Energy” (NUE) becomes available for other purposes, in effect creating the same end-result as the provision of extra electric power, or fresh supplies of fossil fuel. Moreover, NUE is renewable and sustainable, and, once paid for, becomes an almost “free lunch” as long as a building remains operational. There is no element of renunciation; no “saving” with reduced standards or comfort. Extensive surveys of thermal storage are given by McQuiston et al (2000) and by Dincer and Rosen (2002).

Thermal storage promises its substantial contribution to NUE. In fulfilling this promise we believe it necessary for thermal storage to be seen, not just as storage, but in an overall role integrated with the functioning of the building. This means handling of both heat and cold, transport of heat within the building, and heat exchange within the building and with the outdoors. The interaction with the outdoors may take several forms, most typically liquid-to-air heat exchange and solar heating.

2. INTEGRATING THERMAL STORAGE WITH BUILDINGS

The central focus is suitable indoor conditions while compensating for variation in outdoor weather and effects of normal operation of the building, and to do this with a minimum use of energy. The first integrative issue is that this task becomes easier as the building shields its interior through insulation and protection against incipient radiation. All

active, compensating tasks become easier when these passive measures are in place. There is thus not competition between, say, insulation and active measures in the real world, although there may be competition for available funding. The task for thermal storage is made easier with increasing passive measures.

A second integrative issue is transport of heat throughout a building. While in homes and smaller buildings this may be handled on a passive basis, in larger buildings some active form of transport of heat is normally required, for both heating and cooling. This generally involves a mass flow, with the amount of heat transferred:

$$Q = c_v * m * (t_2 - t_1) \quad (1)$$

where

c_v = spec. heat of transfer medium

m = mass of transfer medium

$(t_2 - t_1)$ = temperature drop from transfer medium to receiving medium

Two situations appear to circumvent the temperature drop, although just seemingly so. The first is passive storage like interior walls with appreciable specific heat. Secondly, A/C units with compressor outside and expansion valve and cooling inside, utilize the phase change of the working medium from liquid to vapour. In all other cases, transport of heat relies on a temperature drop in such a way that, for a given amount of energy, half the temperature drop means twice the amount of transfer medium. Although basic this seems often to be forgotten.

Heat transfer normally operates with a heat exchanger supplying heat to the transfer medium (e.g. water) that in turn delivers heat to one or more “radiators”. These perform a key function, and their proper construction and operation are important. With a drop in temperature across the transfer medium of 10 °C for transport of heat proper, temperature drops across each exchanger of 3 °C means a loss of 60 % of net transferred energy. While not a direct part of the present work, it is evident that heat exchangers should be designed with care.

We consider the role of thermal storage in this overall setting. It needs to be dynamic; to transfer heat into and out of storage as required. An idealised solution would be two tanks, each starting half filled, one with warm and one with cold water, and thermally well insulated from each other. A need for heating is met by pumping water from the warm tank, through a radiator and back to the cold tank. Cooling is likewise met by pumping water the other way. The temperature difference is set by the return side not being colder than indoor temperature plus the temperature drop across the radiator, and the high temperature as low as possible to minimise energy consumption. Room temperature at 21 °C, 3 °C drop across the radiator and 10 °C for heat transfer lead to a low temperature of 24 °C and a high of 34 °C. Storage and distribution in this way mean that we use the temperature drop required for heat transfer, for dynamic thermal storage.

3. GAINING ENERGY FROM OUT-DOOR VARIATION IN TEMPERATURE

Practical usefulness is closely linked with variation in outdoor temperature and with heat generation within a given building. An example of variation in outdoor temperature is given in Figure 1:

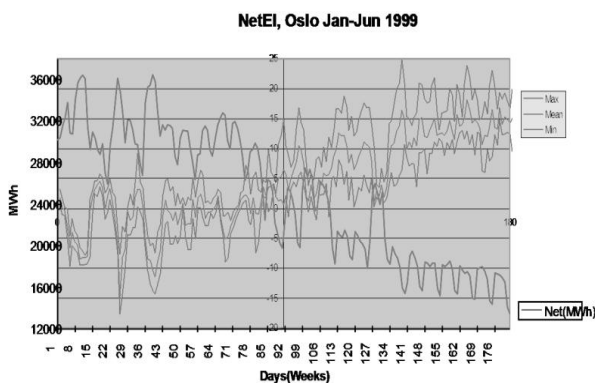


Figure 1: Example of temperature variation and consumption of electric power

Figure 1 shows three dominating mechanisms behind variation in outdoor temperature: annual variation, passage of weather systems, and day/night variation.

Passage of weather systems dominates in winter, with day/night (diurnal) variation becoming significant from early March onwards. Even in cool Scandinavian climates there is substantial need for cooling. Annual variation has a time constant of half a year, passage of weather systems 3 – 5 days, and diurnal variation 12 hours. A fourth factor in Figure 1 is workdays differing from weekends.

Systems for thermal storage need to match these time constants, with larger capacities to match longer intervals of time. Where electric power is used for either heating or cooling, thermal storage promises to make this much more efficient. Electric power is used for heat pumps for air conditioning. Electric power is convenient for direct heating, common in Norway based on cheap, clean hydropower. As described in the Introduction, this picture is changing.

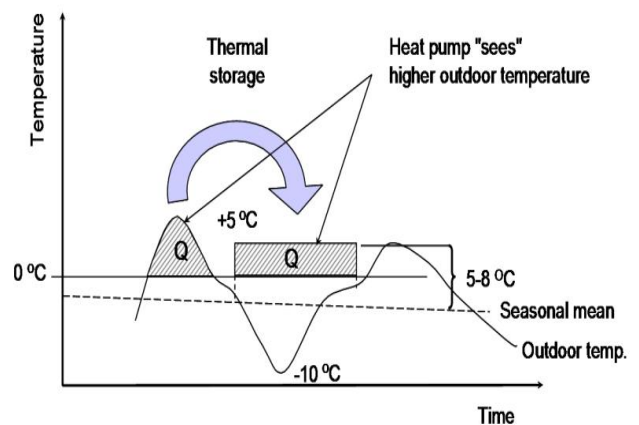


Figure 2: Gaining energy from variation in outdoor temperature

Figure 2 illustrates how dynamic thermal storage (DTS) may be used to obtain energy from natural variation in outdoor temperature. The principle is simple: the heat pump is run at full capacity in mild weather when all of its capacity is not required to heat the building. In a following cold spell heat is obtained from the DTS while the heat pump is turned off. The same reasoning applies to cooling, and in particular to running heat pumps at night rather than in hot summer afternoons (cf. Figure 4 below).

4. COMPUTER-BASED OPTIMISING OF DYNAMIC THERMAL STORAGE

Let us keep in mind the idealised storage with two tanks of water. To exploit a situation like in Figure 2, there must be room for warm water during the mild weather spell. This, in principle, requires that knowledge is available beforehand, and also a mechanism to decide on the issue. Both is available, the first as meteorological forecasts and the latter as PC's (or equivalent specialised electronics). The latter may both obtain information over the Internet, and act on it. Preferably this should run in the background, invisible to users.

Relevant information is the level in the warm water tank, the outdoor temperature, and information on micro-climate, radiation and pattern of use of the building, all on an hourly basis. The software in principle models development of filling level according to running forecasts every 6th hour, based on the building's estimated loss of heat, and will seek to charge the DTS while minimising consumption of electric power. Presumably there are many ways to achieve this. We have found in the present work that the task may be reduced to one of charging in the "best" hours only, where "best" is the outdoor temperature modified according to micro-climate and pattern of use, along with the use of excess heat from the building, heat recovery from spent air in ventilation, and solar heating where and when practical.

Optimisation then reduces to sorting and selection of "hours" from a subset, where the extent of the subset varies with degree of filling of the warm water tank. The system is fastidious if the tank is nearly full, and greedy when close to empty. Practical work as well as modelling are under way and will be reported on separately. Again the picture is parallel for heating and cooling.

5. CONSTRUCTION OF DYNAMIC THERMAL STORAGE

The idealised scheme of two tanks is logically clear, but not practical. We should

seek something that is cheap and simple, as close as possible to established technology, integrated into ordinary construction practice, and as far as possible without moving parts or details that may corrode.

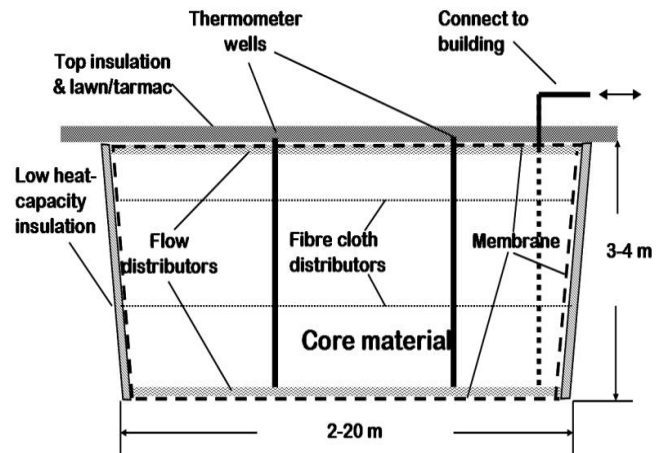


Figure 3: Practical construction of DTS

We have landed on the concept illustrated in Figure 3. This operates on the principles of chemical chromatographic analysis, with warm water in the upper part and cold water at the bottom. Warm water is delivered from the top with cold water entering at the bottom, and the DTS is charged by reversing the flows. The DTS responds to dynamic demand by simply changing the flow-rate or reversing it. This, in turn, is realised by means of positive displacement pumps under variable-speed control that may go via the computer software described previously.

There are three main reasons for a core material: it helps to stabilise warm and cold water as two separate bodies and keep these apart, it provides load-bearing in order that the area atop may be used for something useful, and it helps to stabilise a "hole-in-the-ground" without expensive construction.

The core material consists of expanded clay spheres with a diameter of 4 – 10 mm, and water. Water is partly locked inside the clay spheres, and partly flows past. Some 45 % of total volume is free space. Peak broadening in chromatographic analysis corresponds to mixing of warm and cold water in DTS cores. Three main factors obtain: establishing of equilibrium between moving and stationary phases, diffusion, and

inhomogeneities (e.g. construction detail like vertical beams or walls) that result in “tailing”. This sets a limit to how fast equilibrium may be established, resulting in a maximum linear flow-rate of about 10 mm/minute. This in turn leads to a maximum effect of some 0.3 kW/°C m², with a specific heat capacity of about 3000 kJ/m³. For a typical single home and a 48 hour planning time (cf. above) a core of some 2 – 4 m² cross-section and 5 – 10 m³ of core volume is adequate. Laboratory testing show the zone between warm and cold water to be stable in columns 200 mm wide, over ten days, stretching out to 0.6 – 0.8 m. Dynamic pressure differences are too small to be measured.

A DTS core as illustrated in Figure 3 is under planning and will be reported on separately. It is visualised as a “well” adjacent to the building, some 3 – 4 m deep and with the top available for parking or greenery. The two thermometer wells (constructed from oil-filled plastic tubing with thermo-elements) serve to measure degree of filling of the core (and to set the limit for candidate-hour selection as described in the previous section). The clay material is without sharp edges, and avoids cutting and puncturing to allow ordinary polymer film to be used. A layer of insulating material with low specific heat protects against “chromatographic tailing” from the ground. The clay material is an ordinary construction material (known in Norway as “Leca”), costing about € 40/m³, and with deposition equipment well integrated into construction industry practice.

6. DISCUSSION

Cost and lack of familiarity presently appear to be main reasons that hold back DTS and similar concepts. These two factors together create “Catch 22” – situations where the large scope for lowered costs through learning and through mass production are not realised, keeping up the situation of high costs.

The only way to break out is by means of “self-starters”. With the energy situation

looming as outlined in the Introduction, new solutions could be badly needed on short notice, once the pendulum swings. We should plan for this.

Nothing, we believe, in what is presented in this paper is beyond mass production. The hydraulic complexity is of the same order as modern dish-washing equipment, and is no problem once (even a modest) computer is at hand. The latter is also standard, mass-produced commodities.

The most promising area for mass application is in warm climates addicted to air conditioning, as is now typical in the USA. Enormous amounts of coal are now burnt for electric power for air conditioning. Reducing this would be a real boon to control of CO₂ – emissions to the atmosphere. In the case of coal-based electricity there is a further gain from reducing peak loads that result in lowered efficiency and also increased costs to the generating industry.

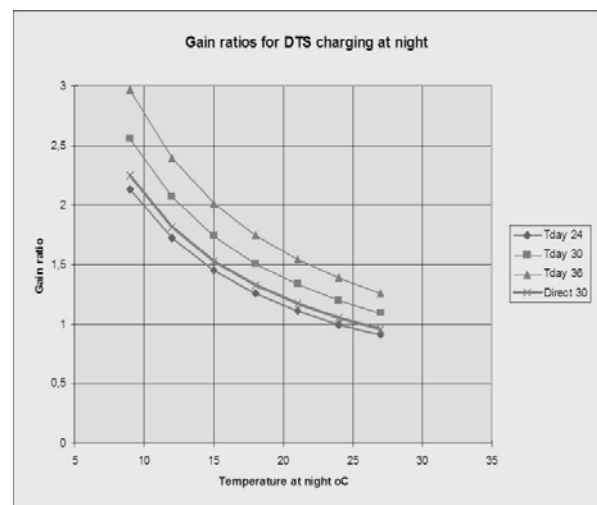


Figure 4: Gains from cooling at night with a DTS-based system

Figure 4 illustrates gains operating DTS-based systems at night, compared to ordinary operation in the afternoon. Assuming a night temperature of 20 °C (for 3 – 5 hours), 36 °C in the afternoon shows a 67 % reduction in energy demand, at 30 in the day the saving is about 45 %, and at 24 °C about 25 %. If the night temperature goes down to about 17 °C, then the heat pump may be dispensed with all together, with a reduction in energy demand

of about 90 %. These numbers apply at the site of cooling. They also obviate all losses up to the excavation of coal.

The last point raises an important issue: *all energy losses upstream are removed with increased energy efficiency at the end-product*. The deep problems of innovation (i.e. the introduction of *qualitatively* new approaches) are addressed i.e. by Nelson (2005).

The thermal generation of electric power may alone waste 50 % or more of the original energy. To this comes transport and processing of coal and losses in the transfer of electric power. Yet this is not seen by the end-user, who just faces a higher bill. This is perhaps where we should focus our attention when facing up to a new energy future.

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