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INTRODUCTION

Heat storage is an essential ingredient in almost every energy conversion system. The batteries in automobiles, the reservoir in a hydroelectric plant, oil stored underground in porous formations, and the coal pile outside a fossil-fuel power plant are examples of storage which are taken for granted. Yet, when it comes to advanced and novel energy systems, people often regard storage as something to be put aside until after the main parts of the system have been studied in detail. Many researchers and scientists do not find storage as interesting or glamorous a topic as, for example, concentrating and collecting solar energy. But a closer examination shows that storage holds challenging problems which need successful solutions before an efficient energy system can be realized. An understanding of the requirements of a storage system, the alternative storage strategies available, and the operating characteristics of available storage systems are of importance to the energy system designer.

This article focuses on those aspects of storage. First, a discussion in general terms of the need for storage points out the characteristics to look for in a candidate storage strategy and describes, in brief, the characteristics of currently available options for energy storage. Second, the techniques used in a specific class of storage devices, namely, heat storage devices, together with their operating characteristics are examined, concluding with a discussion of latent heat storage devices.

THE NEED FOR STORAGE

Energy storage is needed and used for more than one reason. Some of these reasons are intermittence of source, intermittency of load, and starting requirements.

Intermittency of source

The primary energy source may be intermittent in nature. For example, the sun does not shine at night. Therefore, nighttime power needs can be satisfied only by storing excess solar energy collected during the day,

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or by use of a different primary source. If there is only one primary source, storage becomes a must. The function of storage here is to take care of fluctuations in the energy source, which may exist even though the energy demand itself is constant. Without storage, the energy conversion system would have substantial shutdown periods. Any energy converted above the amount demanded by consumers would have to be wasted. Figure 1 shows the energy supply and demand curves for this kind of situation. The best way to provide storage in these circumstances is to have a storage system on the input side of the energy conversion system.

Intermittency of Load

The rate of energy use is never constant, but varies with time in a manner set by the nature of the daily and seasonal changes in those activities that consume energy. If storage capacity is available, the size and, therefore, the cost of the energy conversion equipment can be made substantially smaller. Without storage, the energy conversion equipment would have to be large enough to meet the maximum power demand even though this maximum demand might exist only for a very short period of time. With any capacity less than the maximum, there would be

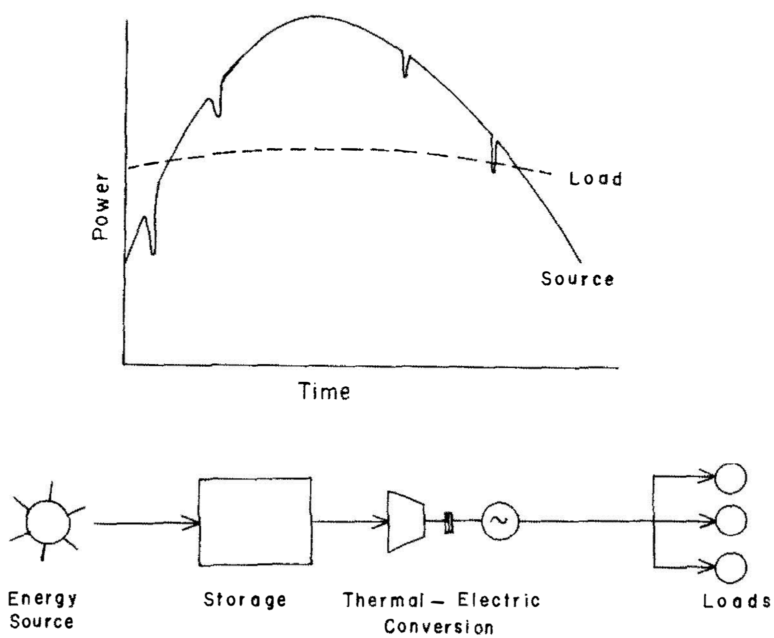

FIGURE 1. Characteristics of Storage System for Intermittent Source

substantial periods of time when the existing demand could not be met. With adequate storage, the equipment would need to be sized only for the average, rather than for the maximum, demand. This kind of requirement for storage is best met by placing the storage system on the output side of the energy conversion system. Figure 2 depicts this scenario.

A good analogy is provided by automobile dealers' new car lots. Without the storage buffer provided by these lots, the production rate in the automobile factories would be directly tied to the day-to-day fluctuations in consumer demand. The number of active workers would fluctuate greatly from hour to hour and day to day. Production lines would have to be established to support the maximum production rate. Much of the time the factory would produce far below capacity, leaving many machines and workers idle. Needless to say, this inefficient way of operating would make the products more expensive. In the same way, not providing storage may lead to greatly increased energy costs.

Starting Requirements

Some type of energy storage is necessary with all power systems which are not self-starting. Automobiles need storage batteries to turn the engines over at the minimum speed necessary for starting. Similarly, fossil fuel

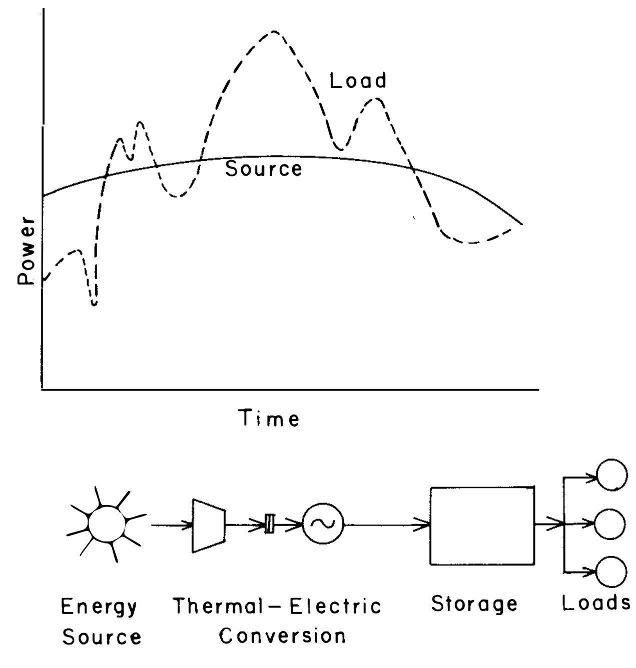

FIGURE 2. Characteristics of Storage System for Intermittent Load

power plants depend on electric motor-driven pumps and other equipment for starting. On the other hand, windmills and electric motors may be considered to be self-starting devices.

Storage Strategy

Intermittence in the energy source is of particular interest for solar energy systems. Here, the ideal location for the storage system is on the input side of the energy conversion system, as has been stated previously. Because most power plants have heat as input, we are led to a study of heat storage.

To meet the needs of the intermittency of load and starting requirements, a storage system on the output side of the energy conversion system is needed. The best solution in this situation is to store work, rather than heat, in one of the various forms. Examples are flywheels for storing kinetic energy, pumped hydro for storing potential energy, and pressure vessels for storing pressure energy in a compressed gas. Of course, there are good reasons for storing energy on the input side, even here. For example, the coal piles and oil storage tanks outside a power station are essentially chemical storage devices, although normally not viewed as such. Here, energy is stored by not burning fuel when it is not needed. Nature has taken care of the storage system for us!

CHARACTERISTICS OF A HEAT STORAGE SYSTEM

Systems which have to convert thermal energy to work, rather than systems which deliver heat as the final product[1] will be the focus of this discussion.

Matching Storage to Power Source

The science of thermodynamics teaches that the most efficient way of transferring heat is to have as little difference as possible between the temperatures of the two substances exchanging heat. Thus, if a power plant uses a Rankine cycle,[2] it is necessary to supply most of the heat to boil a working fluid such as water, converting it into high pressure, high temperature, steam which produces shaft work in a turbine. Because boiling is a constant temperature process, it ensues that the energy storage system must be capable of delivering most of the stored heat at nearly constant temperature. If, on the other hand, the power plant uses the

1. T.S. DEAN, THERMAL STORAGE (1978).

2. A Rankine cycle uses a heat source such as a fuel to produce steam, which drives a steam turbine. The exhaust steam is then condensed and recycled. This is the cycle on which all large fossil fuel and nuclear electric generation plants are based.

Brayton cycle,[3] which is the basis for gas turbine power plants, the working fluid would be a gas such as air or helium. With such a power plant, heat addition to the working fluid is necessarily accompanied by a rise in its temperature. The heat storage system must be able to deliver its stored heat over a whole range of temperatures. Furthermore, its temperature versus stored heat characteristics must closely match the characteristics of the power cycle with which it is associated. Sometimes it becomes difficult to find a storage material which matches well with a given power cycle fluid and at the same time possesses the desirable properties of a storage substance.[4]

These considerations point out something that is often not recognized—that there is no one best heat storage device for all possible uses, and that each power plant cycle has an associated set of good storage devices. Thus, a vapor power cycle may be best served by latent heat storage or thermochemical storage, whereas a gas turbine cycle would find a "sensible" heat storage system more appropriate. A sensible heat storage system is one which stores and discharges heat with an accompanying "sensible" change in temperature. Then, too, a combination of more than one storage device may be needed. For example, after the working fluid in a vapor cycle has been heated into its vapor form, it must be superheated to avoid putting damaging droplets of liquid into the turbine. This may lead to a selection of a sensible heat storage unit working in tandem with a latent heat storage unit, with the latter taking care of boiling the working fluid, and with the former providing the superheating.

Efficiency

There are two important characteristics to be aware of with regard to heat storage devices. The first is efficiency, which is usually defined as the ratio of heat recovered to heat stored. There are two reasons why the efficiency drops below the ideal value of unity. The first is that there will be inevitable heat losses from the outside of any high temperature storage device to the surrounding air. Sufficient insulation must be provided to keep these losses down. The insulation costs should be reasonable. Chemical storage is outstanding in this respect because the chemical products are usually stored at room temperature during inactive periods.

Temperature Degradation

Second, it is unavoidable that the temperature at which energy is discharged will be somewhat lower than the temperature at which it is stored.

3. A Brayton cycle employs air or helium as the working fluid. Atmospheric air is compressed and then heated by burning fuel directly in the air. The hot gases are then expanded in a gas-turbine and exhausted into the atmosphere. Gas pipeline pumping stations and aircraft engines employ gas turbines.

4. R.H. TURNER, HIGH TEMPERATURE THERMAL ENERGY STORAGE (1978).

This occurs because there must be a reasonable temperature difference between the hot and cold substances if we are to accomplish heat transfer through a reasonable heat exchanger surface area. This situation is illustrated in Figure 3. The area under the curves represents the energy stored or discharged. Clearly, the area between the storage and discharge curves represents a loss of "available energy" and brings down the efficiency. The sketches also illustrate why sensible heat storage is more appropriate to a Brayton cycle than to a Rankine cycle, and that the storage system and the energy conversion system must have properly matched characteristics.

Storage Density

Another desirable characteristic of a storage device is high "specific storage," which means the amount of heat it can store per unit weight or per unit volume. For a given storage capacity, high density leads to more compact storage units and reduces the amount of insulation which may be needed. In this regard, it should be kept in mind that storing work instead of heat, if feasible, is another way of reducing the size of the storage unit.

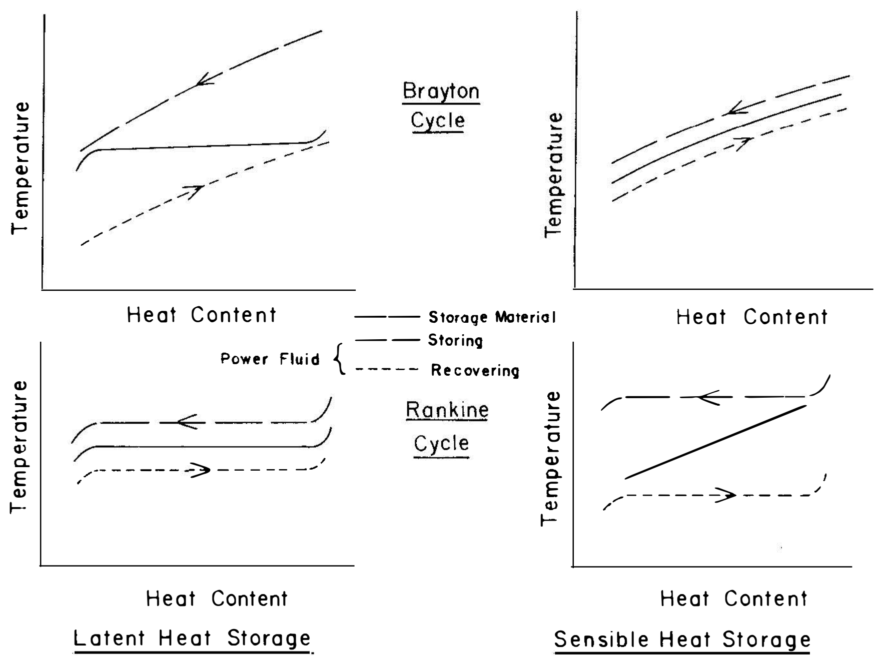

FIGURE 3. Matching Type of Storage System to Type of Power Conversion System

Other desirable characteristics include low cost, reliability, safety, and little degradation after many cycles of operation. The storage materials are all toxic to some degree, and many are corrosive. However, many of them are common chemicals that can be handled and contained safely using existing methods. It is likely that these substances will be used at pressures, temperatures, and environments for which safety standards do not exist. Thus, existing safety procedures and regulations may have to be amended and extended.

DIFFERENT WAYS OF STORING HEAT

The following are some of the ways of storing heat. Each method has its own several specific characteristics.

Sensible Heat Storage

The storage medium is a solid, liquid, or a combination of the two such as rocks and oil, that increases in temperature when heat is stored in it. This storage method is relatively simple and easy to implement, and is being used in the Barstow 10 MW solar central receiver project. However, the specific storage capacity is low, at about 20 Btu/lb for a 100 degree Fahrenheit temperature change. As pointed out above, sensible heat storage is more suited to Brayton cycle power plants because of its inherently non-constant temperature.

Latent heat storage

The storage medium is an inorganic salt mixture or a paraffin wax which stores heat as latent heat of fusion. During storage, the medium is melted. During heat recovery, the medium is made to solidify and thus to give up the stored heat. The specific heat capacity is high, at least 100 Btu/lb. Furthermore, temperature fluctuations between the storage phase, when the storage medium is a trifle cooler than the medium from which it receives heat, and the recovery phase, when the situation is reversed, can be as small as ten to forty degrees Fahrenheit.

Thermochemical Heat Storage

This method of heat storage uses a reversible chemical reaction which is endothermic during storage and exothermic during heat recovery. Very high specific storage capacities can be realized if such a reaction can be found in the right temperature range. A very attractive feature of thermochemical storage is the possibility of using the storage medium as a heat transfer medium as well, which can lead to a "chemical heat pump." Losses during the holding periods between storage and recovery can be practically nil, obviating the insulation required with sensible and latent heat storage. Thermochemical storage requires somewhat more complicated process equipment than latent or sensible heat storage, and catalysts may be required to make some reactions operational. Therefore, thermochemical storage may be indicated as the storage system of choice for large-scale thermal power conversion.

LATENT HEAT STORAGE

Latent heat storage devices can be classified into three groups. They are: (1) passive heat exchangers, (2) active heat exchangers, and (3) direct contact heat exchangers.

Passive Heat Exchangers

These are very similar to the usual fluid-fluid heat exchangers seen throughout a chemical plant. The only difference is that the space occupied by one of the fluids is now filled with the heat storage material, with provision for melting and freezing. Shell-and-tube heat exchangers with finned or unfinned tubes, or plate-fin heat exchangers may be used. Passive heat exchangers are simple in construction and easy to maintain. However, their operating characteristics are not the same as when two fluids are used in the same heat exchanger. An essential difference is that chemical plant heat exchangers operate in a steady state most of the time, whereas a storage unit is inherently unsteady in nature. The usual design and operation charts are not applicable, and the size and spacing of the tubes and fins must be specifically tailored to the latent heat storage application. An off-the-shelf shell-and-tube unit, for example, may perform poorly if the tube spacing is large, because this will allow a thick crust of the storage material to form on the tubes during heat recovery. Because most latent heat storage materials have low thermal conductivities, this crust acts as an insulator and, in time, causes the heat output to fall drastically. Studies have shown that a high latent heat, poorly conducting substance is preferable to a highly conducting material with low latent heat.

New analytical tools and computer programs are now available to design a heat storage unit such that this problem can be avoided. It is also possible to increase the thermal conductivity of the storage material by mixing in metal powder or shavings. These techniques reduce the latent heat of fusion, however, and the optimum mixtures yield thermal conductivities which are higher by a factor of two to five than those of the pure storage material. Much higher effective conductivities can be realized by employing finned tubes. Figure 4 shows a comparison between the operating characteristics of finned and unfinned tubes for a storage

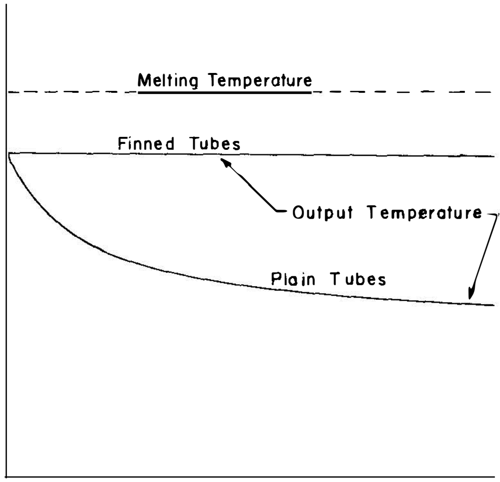

FIGURE 4. Performance of Latent Heat Storage Units with and without Finned Tubes

unit which was to provide auxilliary propulsion for the NASA space station.

Active Heat Exchangers

The idea behind active heat exchangers is to keep the thickness of the crust of frozen heat storage material down by scraping or cutting it off, or by causing the layer to disintegrate by applying centrifugal force. Demonstration units have been built to show that these ideas can be made to work. Nevertheless, these devices are more complicated and require significantly more maintenance than passive heat storage units. The high temperature latent heat materials are all inorganic salts which are usually quite tough and hard and require considerable work input to break and cut.

Direct Contact Heat Exchangers

These do away with the problem of the poorly conducting crust of storage material by keeping it in granular or powdered form, in direct contact with the heat transfer fluid. Sometimes it may be necessary to encapsulate the storage material into small lumps. In principle, this approach is the most efficient from the viewpoint of heat transfer, but it is not easy to find a combination of storage material and heat transfer fluid compatible in direct contact with each other. Researchers have encountered problems of performance degradation after several cycles of operation.

SUMMARY

Storage is an essential part of most advanced thermal systems. Its function is to match the variations in the energy demand to the variations in the energy source. Storage may be provided on the input side or the output side of a thermal-power system, in the form of heat, or in the form of work. There are several techniques for heat storage. Their principles of operation and their characteristics have been described.