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Design and evaluation of a concept for storing thermal energy

K. Andersson, K. Bhandari, S. Chamoun, K. Engel,
KTH, School of Industrial Engineering and Management, Dept. of Machine Design
Email: kan@kth.se, kaviresh@kth.se, schamoun@kth.se, kengel@kth.se

Abstract

Thermal energy storage technology is a promising power source for peak-power requirements in automotive applications as well as for small-scale combined heat-and-power generation. This paper reports project work made in the MF2004 Machine Design advanced course at KTH and describes the design, realization and experimental testing of a concept for storage of thermal energy. The test results were compared to the theoretical model described in the patent application of a steam buffer [1] as developed by RANOTOR AB [2] in Sigtuna, Sweden. The experimental results proved to be in correspondence with the predicted behaviour, which indicates proof of concept.

Keywords: steam buffer, thermal energy storage, waste heat recovery, solar energy

1. Introduction

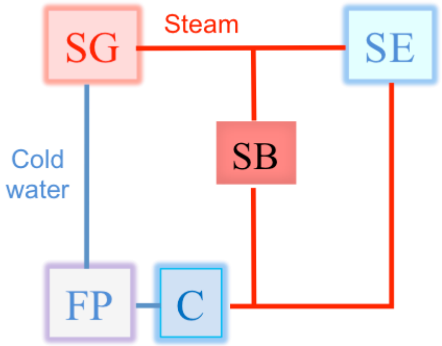
Energy storage is an important technology when intermittent renewable energy is introduced into an energy system. In automotive applications, for example, the concept of energy storage is of growing importance. It is commonly associated with electric batteries; however, there is also a wide range of thermal energy storage mechanisms, which are expected to have greater influence on the product market in the future. One type of thermal energy storage concept, developed by RANOTOR AB, is a so-called steam buffer. It is to be used in a small-scale power system in connection with a reciprocating steam engine, in which steam can be expanded to obtain rotary mechanical power on a shaft.

2. Function and applications

The steam buffer is a device that is charged with thermal energy from a certain energy source and is discharged to generate useful power when this source no longer is available. Favourably, a storage material with high specific heat capacity, such as a ceramic or sand is chosen. The energy to be stored could, for example, be obtained from waste heat in a vehicle. This application implies a need for a compact and lightweight concept. A stationary alternative, which is not limited by size and weight, could receive energy from solar panels. In each of these concepts, even as the source of energy or design of the buffer changes, the function remains the same.

2.1. Power cycle

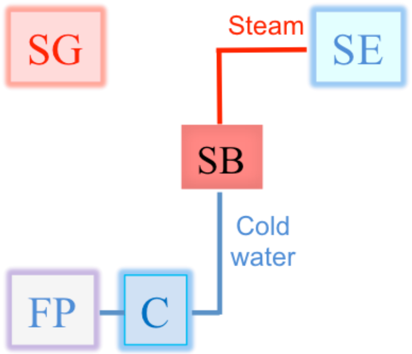
A schematic of the power cycle, in which the steam buffer is to be integrated, is shown in Figure 1.



Notation	Description
SG	Steam generator
SE	Steam engine
SB	Steam buffer
C	Condenser
FP	Feed pump

Figure 1. Schematic sketch of the system

The feed pump supplies cold water to the steam generator, where it is heated to the required temperature. The generated steam can either be led to the steam engine for direct use or through the steam buffer. As the steam moves through the buffer, thermal energy is transferred from the steam to the storage material, hence heating up the buffer and thus storing thermal energy. The steam continues through the buffer, into the condenser, where the steam is cooled to water and led back into the feed pump. This entire process is known as the charging phase of the power cycle. It continues until the steam buffer has reached its maximum storage capacity – at that point, the buffer is said to be fully charged.
When discharging the buffer, a Rankine cycle is realized. The condenser acts as a reservoir of cold water that can be pumped back through the steam buffer. The buffer then transfers its stored heat to the water, converting it to steam, which in turn can be led to the steam engine. This is known as the discharging phase of the cycle and is shown in Figure 2.



Notation	Description
SG	Steam generator
SE	Steam engine
SB	Steam buffer
C	Condenser
FP	Feed pump

Figure 2. Schematic sketch of the system during discharge

2.2. Steam conditions

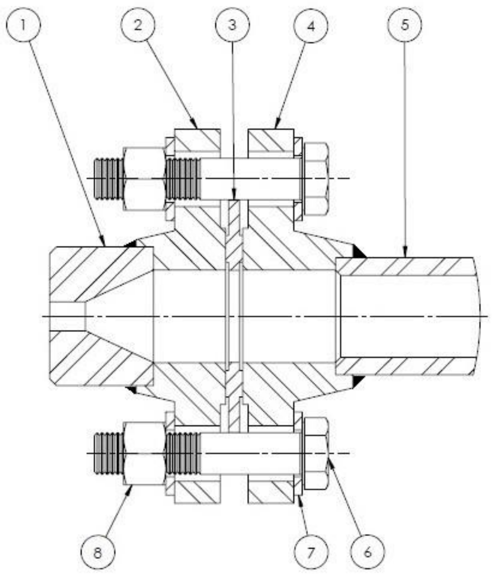
The buffer is designed for steam at 250 bar and 450 °C. At these conditions, the steam is known to be superheated, i.e. all water is vaporised and the steam temperature increases with added heat. The energy density of superheated steam is higher than that of regular or saturated steam, increasing the overall efficiency of the system.

3. Prototype development

A concept of a stationary steam buffer, consisting of a steel pipe filled with sand, was realized. The corresponding CAD-model without the sand is shown in Figure 3.

Figure 3. Illustration of a stationary application concept

For the purpose of sustaining the required conditions, high-grade stainless steel was selected for the specific components of the steam buffer. The main part of the prototype consisted of a Sandvik 7RE10-grade pipe [3]. In order to connect the buffer to the testing system at hand, two end connections were specially manufactured from a Sandvik Sanmac 316L rod [3] and connected to the pipe by use of specific flanges, as shown in detail in Figure 4.



Item no.	Part	Qty.
1	End connection	2
2	End flange	2
3	Gasket	2
4	Pipe flange	2
5	Pipe	1
6	M12 x 1.5 x 60	8
7	Washer	16
8	Nut	8

Figure 4. Drawing of flange connection at one end of the buffer

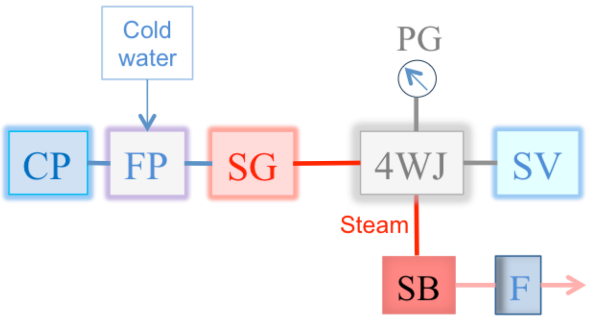
Four ASME B16.5 Class 150 lbs welding neck flanges [3] were modified to match the pressure and temperature conditions. Each set of flanges was then welded to the pipe and end connections respectively. In order to avoid steam leakage from the flange joints, spiral-wound metal gaskets with graphite filling from SpecmaSeals [4] were used. The flanges were ultimately fastened with M12-bolts to obtain a tight seal.

Quartz sand with an average grain size of 0.55 mm [5], a specific heat capacity of approximately 830 J/kgK [6] and low cost in comparison to ceramics was chosen as the energy storing material for the prototype. In order to prevent the sand from spreading to the rest of the system, one-directional stainless steel filters with a pore size of 7 µm [7] were installed at each end of the buffer and subsequently connected to the power cycle.

4. Prototype testing

4.1. Test-rig

The additional components required in the test-rig were provided by RANOTOR AB. Figure 5 shows a schematic of the overall arrangement.



Notation	Description
CP	Compressor
FP	Feed pump
SG	Steam generator
PG	Pressure gauge
4WJ	Four-way junction
SV	Safety valve
SB	Steam buffer
F	Filter

Figure 5. Schematic of the test-rig

The feed pump was operated pneumatically to supply cold water to the steam generator, which in turn used an electric heating element to heat up the water. The steam buffer was thus fed with water of gradually increasing temperature. Continuous heat addition to the water in the generator eventually leads to a flow of superheated steam through the buffer. The heating element of the steam generator was then switched off and water was passed through the steam buffer in order to investigate its discharge cycle. A condenser, as required in the actual power system, was not necessary in this case as the exhaust steam was released into the air and not fed back to the system.
The steam was transferred to and from the buffer using stainless steel pipes, which have a small cross-sectional area, thus able to handle high pressures. These are later referred to as inlet and outlet pipes to the steam generator and buffer.

4.2. Thermocouples

Thermocouples were used to measure the temperature gradient along the buffer. Glass wool insulated thermocouple wires [8] were chosen as they would stand temperatures up to 510 °C. A total of ten wires were plugged into the measurement card and attached evenly along the buffer using hose clips, see Figure 6.

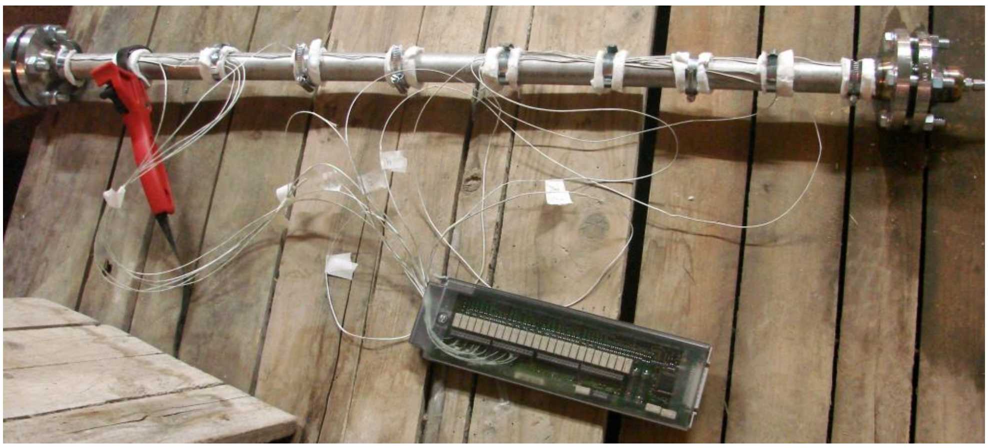


Figure 6. Attachment of the thermocouple wires to the buffer and to the measurement card

5. Test results and analysis

5.1. Flow rate and pressure tests

The buffer was filled with approximately 1 kg of quartz sand. Thereafter, a number of sample tests were performed to examine the flow rate and pressure difference across the steam generator and the attached components. The first three tests were performed without adding heat. The pressure difference between the point of steam generation and the exhaust of the steam buffer was measured using an analogue pressure gauge and was recorded at a maximum of 50 bar. The results from the initial three tests as well as the final test, where heat was added to the buffer, are summarized in Table 1.

Table 1. Prototype testing conditions

Test no.	Components attached to steam generator	Pressure difference (bar)	Flow rate (ml/s)	Remark
1	Inlet pipe, buffer	~ 0.1	4.30	No sand at the buffer outlet, no heat added
2	Inlet pipe, buffer, outlet pipe	30	2.94	No sand at the buffer outlet, no heat added
3	Inlet pipe, buffer, outlet pipe, filter	50	2.88	No sand at the buffer outlet, no heat added
4	Inlet pipe, buffer, outlet pipe, filter	50	1.88	No sand at the buffer outlet, 3 kW into steam generator

The following test results correspond to the conditions of test no. 4 above, with a pressure and temperature of approximately 50 bar and 200 °C.

5.2. Temperature measurements

Thermocouple no. 1 was attached closest to the buffer inlet and thermocouple no. 10 closest to the buffer outlet. The initial temperature of the steam buffer was approximately 12 °C. After continuous heat addition from the steam generator, the buffer was charged within 15 minutes to a final temperature of 201.7 °C. At this point, cold water was added to the buffer, initiating the discharging phase and leading to a decreasing temperature gradient over time. The obtained temperature profiles for the respective thermocouples are shown in Figure 7.

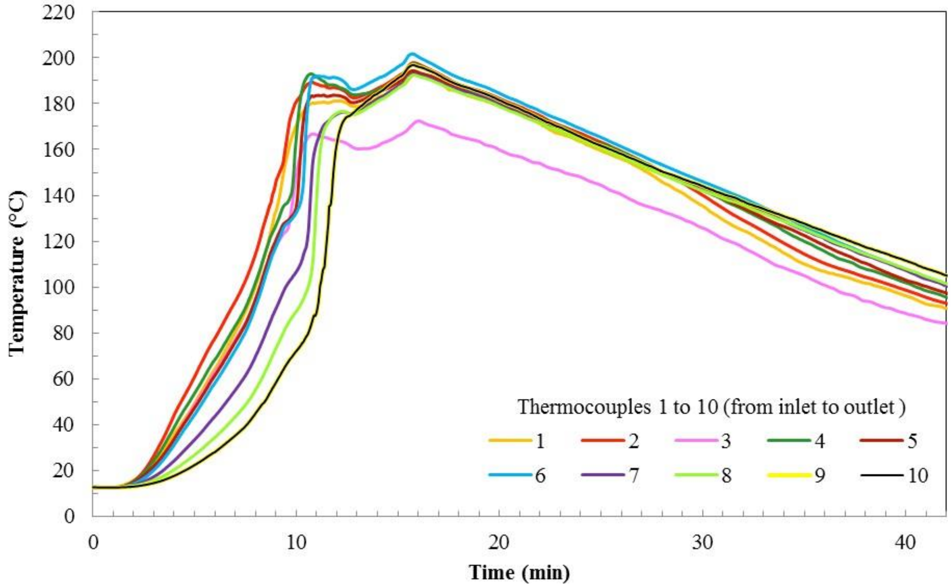
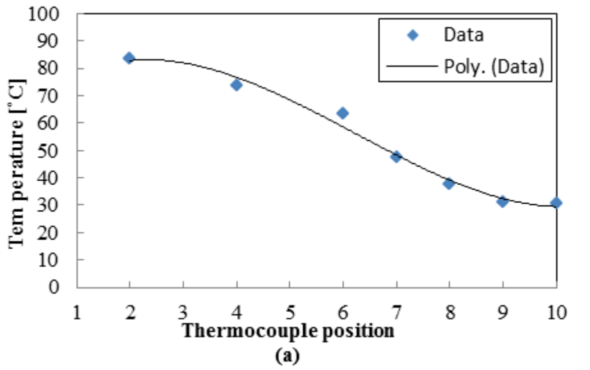


Figure 7. Temperature profile of each thermocouple along the steam buffer

It was observed, that, as cold water was added to the charged buffer, steam was being generated at its outlet, hence proving the functionality of the patented concept.
It can be seen that the curves maintain a certain slope up until 100 °C. Thereafter, the temperature gradients steepen, due to the two-phase condition of the steam. The graph indicates

that the temperature profile of thermocouple no. 3 deviates considerably from the expected behaviour as compared to the profiles of the other thermocouples; its curve lies approximately 20 °C below the others. Also, thermocouples no. 1 and 5 indicated values that did not quite correspond to the predictions. Hence, the measurement data obtained with these thermocouples was not considered.

An interesting observation concerning the steam buffer is the thermal development during its charging and discharging phase. Figure 8 (a) shows the empirically determined temperature gradient along the buffer six minutes after the start of its charging phase. For comparison, the theoretical behaviour as predicted by Platell [1] is shown in Figure 8 (b), with the arrow indicating the charging direction.



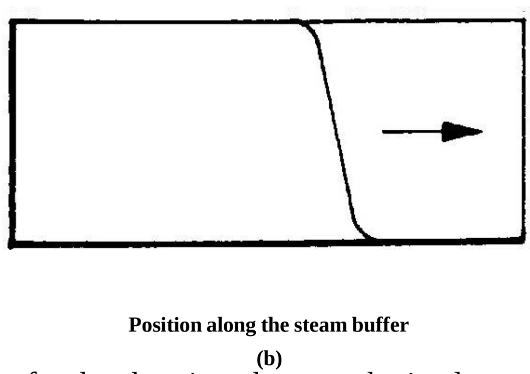
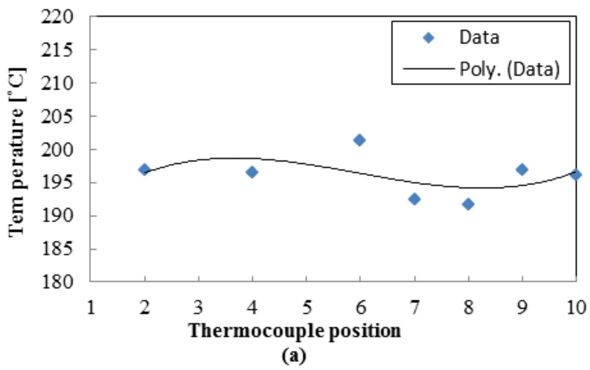


Figure 8. Temperature gradient along the buffer for the charging phase as obtained (a) experimentally and (b) theoretically (edited from [1] to match inlet direction)

As shown, the behaviour of the tested prototype coincides with the theoretical prediction. Figure 9 (a) shows the empirically determined temperature gradient along the buffer as it is fully charged, approximately 15 minutes after the start of its charging phase. For comparison, the theoretical behaviour as predicted by Platell [1] is shown in Figure 9 (b).



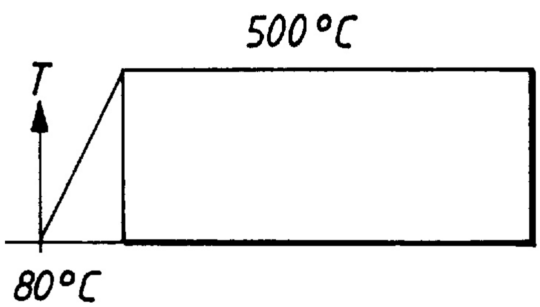


Figure 9. Temperature gradient along the buffer as it is fully charged as obtained (a) experimentally and (b) theoretically [1]

The narrow temperature span of Figure 9 (a) indicates that the buffer has an almost constant temperature along its length. The apparent sinusoidal nature of the data points is partly due to the variance in measurement sensitivity and partly due to the lack of insulation around the thermocouples during initial testing. However, if set to scale, the data points correspond well with Figure 9 (b), which shows a theoretical graph of a fully charged steam buffer.

Figure 10 (a) shows the empirically determined temperature gradient along the buffer during its discharging phase, 40 minutes after start of the test. In comparison, the theoretical behaviour as predicted by Platell [1] is shown in Figure 10 (b), with the arrow indicating the discharge direction.

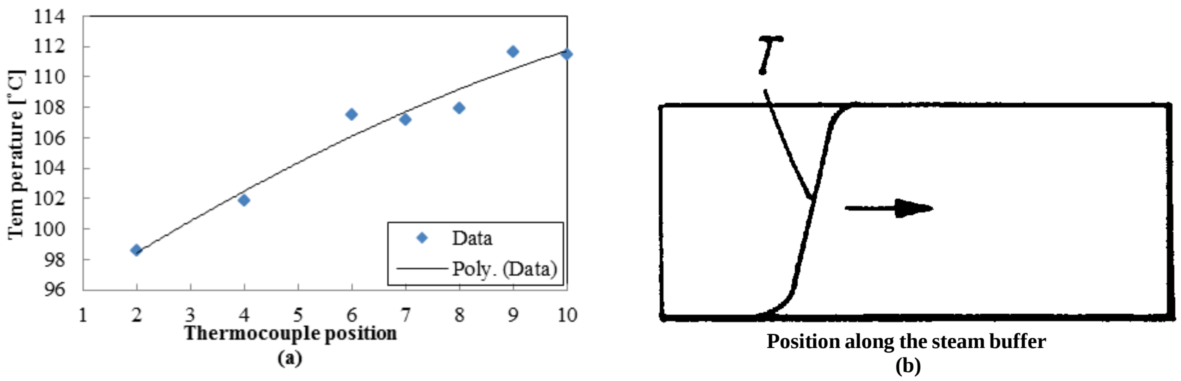


Figure 10. Temperature gradient along the buffer for the discharging phase as obtained (a) experimentally and (b) theoretically [1]

As cold water was added to the inlet of the buffer, the temperature decreased gradually from the inlet to the outlet. In this process, the sand lost its stored energy to the cold water, thus producing steam.

6. Conclusions

This paper describes the design, realization and experimental testing of a concept for storage of thermal energy. The developed prototype was tested at the facilities of RANOTOR AB and the results proved to be satisfactory, i.e. in correspondence with the predicted values in the patent application [1], which indicates proof of concept. After continuous heat addition from the steam generator, the buffer was charged within 15 minutes to a temperature of approximately 200 °C. Thereafter, cold water was added and the temperature gradient was observed to decrease gradually. Steam was generated at the outlet while cold water was added to the buffer, hence proving the functionality of the steam buffer. Additional development of the various concepts is to be performed. This includes elaboration of the presented designs, purchase of appropriate components and materials and further testing.

7. Discussion

The buffer has been designed to withstand a pressure of 250 bar at 450 °C. However, the tests were conducted at a pressure of only 50 bar and a maximum temperature of 200 °C in order to rule out any hazard and risks. Future tests are proposed to be conducted at higher temperature and pressure in order to comply more accurately with the theoretical model.

Further, the use of filters at each end of the steam buffer was intended to hinder the sand from flowing out of the buffer at high inlet pressures of steam or cold water. However, performing some initial tests confirmed that sand did not flow out of the buffer at a pressure of 50 bar. The sand had been pre-soaked in water, leading to probable void spaces from which the steam could escape, implying that the sand had settled in the pipe. Hence, it was inferred that the sand had not been packed tightly enough in the buffer.

The buffer was discharged by adding water to its inlet. Here, the water passed through the steam generator again, which was still warm after having been switched off, leading to a discharge with initially warm water as oppose to cold water. Also, the water was fed into the buffer from the inlet; however, the discharge cycle is intended to move from the buffer outlet to the inlet (as previously shown in Figure 2). It is recommended to rearrange the test-rig to not only be able to feed the buffer with cold water but also feed it from the correct direction, i.e. from the buffer outlet.

The buffer was not completely insulated while testing. Instead, glass-wool strips were used to only insulate the thermocouple elements. The data measured by the thermocouples was observed and it was noted that the thermocouples no. 1, 3 and 5 did not record the temperatures as expected. Thermocouple no. 1 may have measured lower temperatures due to the weld between the pipe flange and the pipe. It can be inferred that the heat-affected zone due to the weld changed the thermal properties of the steel pipe around the weld. Thermocouples no. 3 and 5 seem not to have been properly secured with the insulation and hose clip, hence not measuring accurate temperatures.

The following procedures are suggested for future testing:

- Charging the buffer and allowing it to cool down itself in order to infer the rate at which the buffer discharges, as well as to measure the total time of energy storage.
- Adding a throttle valve at the outlet of the buffer to increase the pressure within the buffer.
- Using a bi-directional filter at the inlet and outlet of the steam buffer would enable flow in both directions. Such a filter, meeting condition requirements is not available "off-the-shelf" according to the literature reviewed and might need to be specially developed.

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