Performance of heat pipes as capillary pumps: experiments

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Abstract This paper describes the development of an experimental setup to investigate the performance of heat pipes as capillary pumps. The experimental setup and the research that was performed by LFME was part of an EU funded research project called TRI-GEN EGD that aims in the overall development of a novel Tri-generation Electrogasdynamic converter system. The capillary pump will be used to pump the working fluid of the system using external waste heat. Furthermore, since the capillary pump has no moving parts it will provide the system with greater reliability. The experimental setup designed and constructed by LFME is a Capillary Pumped Loop (CPL). A CPL is a closed loop system that pumps liquid by passive means, based on the operating principles of heat pipes. Specifically capillary forces are generated on a porous structure that exists in the evaporation section and is responsible for pushing the working fluid from a high temperature source to a low temperature sink. In this paper, a brief description of the experimental setup that was constructed and a description of the experimental procedure that was followed will be given together with some results that were obtained for various configurations.

Keywords capillary pumps; CPL; electrogasdynamic converter system

1. Introduction

The work described in this paper was carried out as part of the EU funded research project, TRI-GEN EGD, which aims at the development of a novel Tri-generation Electrogasdynamic converter (TRI-GEN EGD) system and completes the work presented in a previous publication [1]. The TRI-GEN EGD system could be used to provide electricity, cooling and heating for buildings and industrial applications. It is based on the integration of an ejector refrigeration cycle with an electrogasdynamic (EGD) energy converter which is used to convert thermal energy into electrical power. The system could employ ‘ozone-friendly’ refrigerants such as water, methanol, ethanol, hydrocarbons or hydrofluorouoethers (HFEs). In addition, the system has no moving parts and both ejector and EGD converter would be simple and reliable. The anticipated cost of production is low since inexpensive construction materials (e.g. copper or aluminium) could be used.

The capillary pump of the TRI-GEN EGD system, investigated by the Laboratory of Fluid Mechanics and Energy (LFME) and presented in this paper, could be used to pump the working fluid of the system using external waste heat. The operation of the capillary pump is based on a Capillary Pumped Loop (CPL) system.
To this end, the present paper is structured as follows: initially a general description of the TRI-GEN EGD system is given and a brief introduction to CPLs is given in order to familiarize the reader with the technology being used. Next, a detailed description of the experimental setup is given together with a description of the instruments that are used. The experimental procedure will then be described and finally some results will be presented.

2. General description of the TRI-GEN EGD system and background theory on CPLs

2.1 General description of the TRI-GEN EGD

As mentioned, the TRI-GEN EGD (Fig. 1a) system could be used to provide electricity, cooling and heating for buildings and industrial applications as indicated in [2] and [3]. The proposed system consists of an EGD ejector unit (single nozzle or multi nozzle), a capillary pump generator (which is considered as the primary vapour generator using an external heat source, such as waste heat for example), a condenser and a secondary evaporator used to create the cooling effect. The capillary pump generator uses the outer loop and the secondary evaporator uses the inner loop as shown in Figure 1a. The proposed system has no moving parts thus making it more robust and at the same time minimising the creation of noise and vibration.

The EGD converter part for creating electricity (Fig. 1b) consists of a corona electrode, a Venturi nozzle combined with an attractor electrode, and a condenser integrated with a collector electrode and works in the following way: initially the working fluid is vaporised in the capillary pump generator and the vapour flows to the Venturi nozzle, expanding and partially condensing. As the under-saturated vapour passes through the space between the corona and the attractor electrodes at a high speed, the created liquid droplets are charged due to the high electrostatic field and form a charged aerosol. As this high speed charged aerosol flows through the electrical field existing between the two electrodes, the kinetic energy is converted to electrical power. After discharge, the neutral aerosol condenses by cooling and the liquid working fluid is in turn pumped back to the vapour generator.

In order for the system to incorporate cooling in addition to electricity production, the EGD converter part also contains an injection nozzle, a mixing section and a diffuser. After passing through the nozzle, the high pressure vapour expands to a high velocity and low pressure stream which combines with low-pressure vapours from the secondary evaporator causing a cooling effect. Both streams mix and diffuse to a higher pressure and condense in the condenser, which is placed right after the diffuser.

From the above described procedure it can be clearly seen that the system can be used to produce electricity and provide heating and cooling simultaneously.

Furthermore, as indicated above, there are no moving parts in the described system. Thus, with the introduction of a capillary circulation pump, the system would be completely passive. Such a pump would also reduce the number of components for the whole system because at the same time the working fluid would be pumped and vaporised, thus there would be no need for an additional generator in
the system. Up to now such pumps have only been used in the context of Capillary Pumped Loops (CPLs) and Loop Heat Pipes (LHPs) in which cases the operation is specifically oriented to transferring heat using a working fluid while in the present case the operation is specifically oriented towards pumping of the working fluid.

2.2 General theory on CPLs
A CPL is a closed loop system which uses passive means to pump its working fluid as mentioned in [4] to [13]. Its operating principle is based on the existence of capillary forces within a porous or wick structure in the evaporation section. These capillary forces are responsible for pushing the working fluid from a higher temperature area of the loop to a lower temperature area. The main difference from the heat pipes is that a wick/porous structure is needed only in the evaporator section of the CPL. CPLs are considered as reliable thermal management devices and are widely used.
for cooling electronic components. Furthermore, because of their passive nature, CPLs are especially used in space applications.

In Figure 2, the basic components of a typical CPL are shown. These components are:

- an evaporator zone,
- a vapour transport line,
- a condenser zone,
- a liquid return line,
- a reservoir.

Heat is provided through the evaporator which in turn vaporises the working fluid, while the condenser removes heat and condenses the fluid. The vapour transport line and the liquid return line transfer vapour and liquid, respectively, between the evaporator zone and the condenser zone. The reservoir, also known as the compensation tank, is used for controlling the operating temperature and also as for liquid inventory management.

Assuming that the loop is completely filled only with the working fluid in its liquid state, the evaporator is heated. As mentioned, the evaporator contains a porous or wick structure, which at this point has been completely filled with the working fluid. Thus when heat is initially applied, the liquid in the wick structure starts to evaporate and the capillary forces at the vapour/liquid interface start to develop. The vapour of the working fluid is then transferred through the vapour transport line to the condenser section where it is cooled and condensed. At the end of the condenser section, the liquid is subcooled to ensure that it will not vaporise before completing the cycle and reaching the evaporator section. Finally, through the liquid return line, the working fluid is returned to the evaporator and the cycle is repeated.
3. Experimental setup and procedures

3.1 Experimental setup
Initially the experimental setup consisted of a 70 cm long sintered material filled pipe and the liquid/vapour sections of the setup were approximately 7 m long (Fig. 3). However, after some experience had been gained in starting up the system, it was decided to try a smaller/shorter configuration. This led to a reduction of the experimental setup to about one-third its initial size, i.e., liquid/vapour sections about 2.5 m long (Fig. 4).

Furthermore, in order to increase the flowrate, multiple, parallel evaporator configurations were tried in addition to the single sintered material filled pipe. Specifically, three 15 cm long evaporator configurations, consisting of 1, 3 and 7 sintered material filled pipes, respectively, bundled together were built.

After performing the tests on the 15 cm long pipes, LFME decided to further reduce the size of the pipe used. The configuration of sintered material filled pipes that is currently being used is 2 cm long (Fig. 5) and consisting of a bundle of 3 pipes (Fig. 6). A single 2 cm pipe and 4 parallel 2-cm pipes have also been tested. Below follows a description of the most recent setup that was tested.

The diagram of the experimental setup designed and developed by LFME is given in Fig. 7. The description of its main components follows the numbering shown in Fig. 7:

![Initial configuration of the experimental setup with the 70 cm sintered material filled pipe.](https://academic.oup.com/ijlct/article-abstract/2/1/30/787537 by guest on 25 December 2018)
Figure 4. Current configuration of the experimental setup with the 3–2 cm long sintered material filled pipes.

Figure 5. Bundle of 3–2 cm long sintered material filled pipe.
1. 10 litre compensation tank that contains a 1500 Watt heating resistor which is connected to an analogue thermostat for controlling the temperature of the water. The compensation tank is also equipped with a 0.5 m long high pressure, heat resistant glass tube in order to monitor the level of water in the tank.

2, 3, 10, 11, 12, 23 and 24. Ball valves for managing the filling up, start up and operation of the system.

4. Filter for removing impurities from the working fluid.

21. Kobold KDF-1125-NV flowmeter that has a measuring range of 1.2 lt/h to 12 lt/h, with maximum operating temperature of 80°C and maximum operating pressure of 10 bar. The flowmeter works on the following known principle of rotameter flowmeters: a float (stainless steel ball) is placed inside a cone-shaped measuring glass. The float is raised due to drag forces to a certain level in proportion to the flow velocity of the medium.
5 and 9. Kobold MAN-SF26 pressure gauges, P1 and P2, respectively, each with a cooling element. The operating pressure range is from 0 to 7 bar and the operating temperature range is $-20$ to $85^\circ$C. The cooling element was placed to protect the pressure gauge from a medium that would have a temperature higher than $85^\circ$C. These pressure gauges are used to measure the pressure of the working fluid before and after the evaporator section (sintered material filled pipe).

6, 8, 13 and 14. Kobold TSA1105 Pt100 thermocouples, T1, T2, T3 and T4, respectively, used to measure the temperature of the liquid/vapour at the corresponding points. The maximum operating pressure of the thermocouple is 16 bar and the temperature range it can measure is $-60$ to $180^\circ$C.

7. The sintered material filled pipes and the heating coil, without the insulation material placed. The heating coil is placed snugly around 1/3 of the pipe, downstream.

15. 10 litre suction tank. The purpose of the suction tank is to assist in achieving a high start-up temperature for the whole system.

16 and 17. Kobold TWA R6A 03012P thermocouples placed on the surface, on each side of the sintered material filled pipe, with measuring range of $-50$ to $260^\circ$C, to monitor the temperature at the corresponding points.

18. Kobold TWA R6A 03012 placed on the surface of the pipe in order to monitor the temperature at the condenser section.

19. DVP LA 12 vacuum pump for generating the required vacuum in the system before its filling up with the working fluid.

Figure 7. Diagram of the experimental setup indicating the position of major components.
The electronic flowmeter type Kobold KMI-1209HN2A40, has a measuring range of 6 lt/h to 60 lt/h, with maximum operating temperature of 120°C and maximum operating pressure of 100 bar. The flowmeter is placed vertically and the position of the float inside the measuring tube is transferred to a large side indicator by means of a magnetic field.

This is a one way valve that allows fluid motion only in the direction of the liquid line and not in the direction of the vapour line.

For the CPL under investigation it was initially decided to use stainless steel pipes without however excluding the use of copper or aluminium in the future, as mentioned in the introduction for the whole TRI-GEN EGD system. The pipes loop is made of 1/2 inch stainless steel pipe which can withstand pressures up to 12 bars. All pipe connections are sealed with Loxeal 18-10 liquid which when solidified can withstand pressures up to 60 bar and temperatures from −50 to 150°C. The liquid is fully compatible with the working fluid being used, which is water.

The majority of the loop is insulated by means of a special ceramic material very similar to that used in fireproof blankets. The material is used to assure that the system is not affected by external fluctuations of temperature. The same material is also used around the heating coil and can withstand temperatures up to 1350°C without igniting.

Finally, as mentioned above, all pressure and temperature sensors are connected to a PC-based data acquisition system for continuous monitoring on the PC monitor and simultaneous digitization and storing. The software for the data acquisition was developed by LFME specifically for the needs of the project and is based on the well known software package called Labview (version 6i). The hardware of the data acquisition system consisted of a Pentium II PC with a 233MHz CPU and 256 MB of RAM memory. The PC was equipped with a National Instruments PCI-MIO-16E-4 data acquisition card. For further information about the software and the data acquisition card, the reader is advised to visit the National Instruments website: http://www.ni.com

### 3.2 Experimental procedure

Initially, the compensation tank is filled with distilled water in order to avoid having blocking phenomena later on in the sintered powder material due the presence of various unwanted minerals and salts in the water, and its temperature is brought to the desired level.

During the heating of the water in the compensation tank, the vacuum pump is turned on until the desired level of vacuum has been achieved in the pipe system and the vacuum tank.

Then, with appropriate sequencing of the opening/closing of the ball valves 2, 3, 10, 11, 12, 23 and 24, the pipe system and the sintered material filled pipes are filled with heated water from the compensation tank. In this operation, the purpose of the suction tank is to assist in filling up the system with high temperature water, needed for the start up.
Once the system is filled with high temperature water, the heating coil on the sintered powder material filled pipe is turned on. The temperature on the surface of the evaporator at its entrance and exit is monitored with the thermocouples 16 and 17, respectively. The pressure and the temperature of the water at the entrance to the evaporator and of the vapour at its exit are monitored with the pressure gauge and thermocouples 5 and 6, and 9 and 8, respectively.

The temperature at the entrance, centre and exit of the condenser is monitored with the thermocouples 13, 18 and 14, respectively.

Finally, the initiation of the flow and its subsequent development is monitored from flowmeters 4 and 20 and by observing the behaviour of the level of the water in the glass tube of the compensation tank 1.

The whole experiment, from the heating of the compensation tank to the observation of periodic flow, for at least an hour, required a minimum of four to five hours to be performed.

4. Results

Regarding the 15 cm long pipe configurations the following was observed:

**Single pipe configuration.** Oscillations of the water in the glass tube of the compensation tank were observed, which at times were rather strong reaching 5 cm peak to peak. The ball in the flow meter started rising and falling periodically, indicating flow, but with frequency less than that of the oscillations of the water in the glass tube after isolating the compensation tank from the pipe loop, the oscillations of the ball in the flowmeter became stronger and more regular, indicating peak flow velocities between 1.2 to 2 lt/hr.

**3-pipe configuration.** The bundle of 3 pipes filled with sintered material achieved larger peak velocities and were more stable compared to the single pipe configuration.

**7-pipe configuration.** The bundle of 7 pipes filled with sintered material also achieved larger peak velocities but provided an unsteady flow compared to the single and triple pipe configurations.

Regarding the 2 cm long pipe configurations the following was observed:

**Single pipe configuration.** The single 2 cm long sintered material filled pipe achieved the best flow rates observed so far. Even though they were not totally periodic, the flowmeter showed indications of flows reaching 12 lt/hr, which is the maximum of the installed flowmeter.

**4-parallel pipes configuration.** In this configuration 4 pipes containing 2 cm sintered filled material pipes were placed in parallel. Initially the system started well with flowrates periodically reaching a value of 8 lt/hr, however after some time steam
would start flowing in the opposite direction through one of the parallel pipes thus stopping all liquid flow in the system.

**Triple pipe configuration.** The bundle of triple 2 cm long sintered material filled pipes achieved the steadiest periodical flow ever observed. The flowrates did not exceed 6 lt/hr, however for the whole time that the system was running under steady state temperature conditions there was a periodical flow in the system in the range of 2 to 4 lt/hr.

The following figure (Fig. 8) is a compilation of the measurements obtained from one of the triple pipe experiments that were performed. Before presenting these results, it should be noted that the setup under examination was not fully insulated during the experiment and that the average heat provided by the heating coil was 300 Watt. Furthermore, the flow values are average values for a specific series of time steps. This means that at no time was steady flow observed in the system, as it will be seen in the graph, but only “spikes” of flow were observed. However, due to the fact that the electronic flow meter was not in a position to measure the flow, all numbers were obtained from the video tape that was used to simultaneously record the flow in the glass flowmeter together with the pressure and temperature measurements that were being logged on the PC. Thus after the experiment, the video tape was reviewed and the flow measurements were noted and compiled together with the other data that was logged. An average value had to be used because flow values could only be distinguished on a minute per minute basis and not on a second per second (or 5 second per 5 second as indicated in the graph) basis, thus e.g. if there were three different changes of flow in a minute and measurements were obtained for 1 minute at a 5 second interval, then an average flow value was considered for the first 4 points, another average was considered for the second 4 points and a third was considered for the last 4 points.

In the graph presented above we notice that the T2 and T3 temperatures during the whole time of periodic flow, are very close and at about 100°C, which means that steam is constantly being created in the vapour side of the setup. In the beginning, before the stabilization of temperatures T2 and T3 we notice that large flowrates are observed, but they are rather more like spikes and do not have a periodic nature. When temperatures stabilize, the periodic flowrate observed is between 1 and 2 lt/hr. On the liquid side of the setup, temperatures are also constant, T1 and T4. For T4 we notice that it starts a bit high, around 45°C and then it drops to an average of 30°C. This is due to the fact that the refrigerator was not used from the beginning of the experiment for the cooling of the vapour line, but only after the temperature in T3 exceeded 75°C. At the same time, on the exterior of the setup we notice that the temperatures on the left and right side of the sintered material filled pipes are quite stable and there is an average difference of 30°C. Regarding the thermal resistance it should be indicated that it is higher compared to the open literature (i.e. [4] and [5]) due to the relatively large volume of the working fluid and its large thermal capacity (water).

Concerning the pressures, we notice that P1 is more stable than P2, however they both have a similar response during the whole experimental duration. The continu-
ous changes in P2 show that steam is being created continuously during the duration of the experiment. It can also been seen that at all times P1 is slightly greater than P2. The large step that is seen at Time Step 250 can be explained by the fact that at that certain point the heater in the compensation tank turned on and the tem-

Figure 8. Compilation of the measurements obtained from one of the triple pipe experiments that were performed.
perature in the tank rose, as can be seen by the Tank temperature curve, thus leading to a total rise in pressure of the whole system of about 0.15 bar.

Similar results have been obtained for various experimental runs, thus showing that the sintered material filled pipe is able to create a certain amount of flow.

5. Conclusions

From the experimental results presented it can be clearly seen that there is a strong potential for the sintered material filled pipes to work as capillary pumps. When working under steady state conditions there is a constant periodical flow in the system at an average value of 2 lt/hr. Fine tuning of the system together with the use of another working fluid with a lower boiling temperature will be able to provide a constant, steady and much higher flowrate.

Finally, at this point it should be mentioned that a theoretical model of the experimental setup was developed and the results presented above are in good agreement with those estimated by the model in [14].

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References


