Development of a Solar Cooling System Based on a Fluid Piston Convertor

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Abstract
Solar water pumping and dynamic water desalination based on fluid piston converter were developed at Northumbria University. The fluid piston converter has a simple design and made of low cost materials. In water pump and desalination systems, the fluid piston converter works as an engine, driven by solar thermal energy absorbed by flat-plate or evacuated tube collectors. If in the same design of the converter, its fluid piston is driven using external source of energy without heat input, then such the converter works as a cooling device.

In this study, the solar fluid piston engine is coupled with the cooling unit with the fluid piston of the latter driven by the fluid piston engine. This results in production of cooling effect using solar energy. The operation of such system has been investigated theoretically and experimentally. The thermodynamic model, consisting of a system of ordinary differential equations, was developed in the MATLAB/Simulink environment to simulate the operation of such the thermal auto-oscillation system. The theoretical results confirm that it is possible to achieve the temperature of the working fluid in the cycle of the cooling unit, which is below the ambient temperature. The cooling effect depends on the operational parameters of both the engine and cooling parts of the system.

Keywords: solar cooling system, fluid piston engine

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Nomenclature

Symbols

C_v - specific heat at constant volume
M - mass
P - pressure
$\dot{Q}$ - heat transfer rate
t - time
V - volume
γ - isentropic index
ω - angular velocity
C_P - specific heat at constant pressure
$\dot{m}$ - mass flow rate
p - denotes to fluid piston engine control volume
R - universal gas constant
T - temperature
X - displacement of the water level
ε - the cooler effectiveness

Indexes

c - denotes to the cooler control volume
e - denotes to cooling space control volume

Introduction

At present, a limited number of solar cooling systems are available commercially on the market and the scale of the practical applications is relatively small due to relatively high initial and running costs. Numerous studies have been carried out on different types of solar cooling systems including solar absorption and adsorption systems [1-5], the combined power and cooling [6, 7] and other types of solar cooling systems [8-10]. During the last few years, new test rigs for solar water pumping and dynamic water desalination unit were built and experimentally and theoretically investigated at Nortumbria University [11, 12]. These test rigs were built around the fluid piston converter/engine and solar evacuated tube collector with heat pipes. Heat input into the system was carried out using a solar simulator, made of 110 halogen floodlights, and controlled by an electrical three-phase transformer.

The concept of solar cooling system which has been built around the fluid piston engine and cooling machine is shown in Figure 1. The solar energy is used to drive the fluid piston engine which in its turn drives the cooling machine producing a cooling effect.

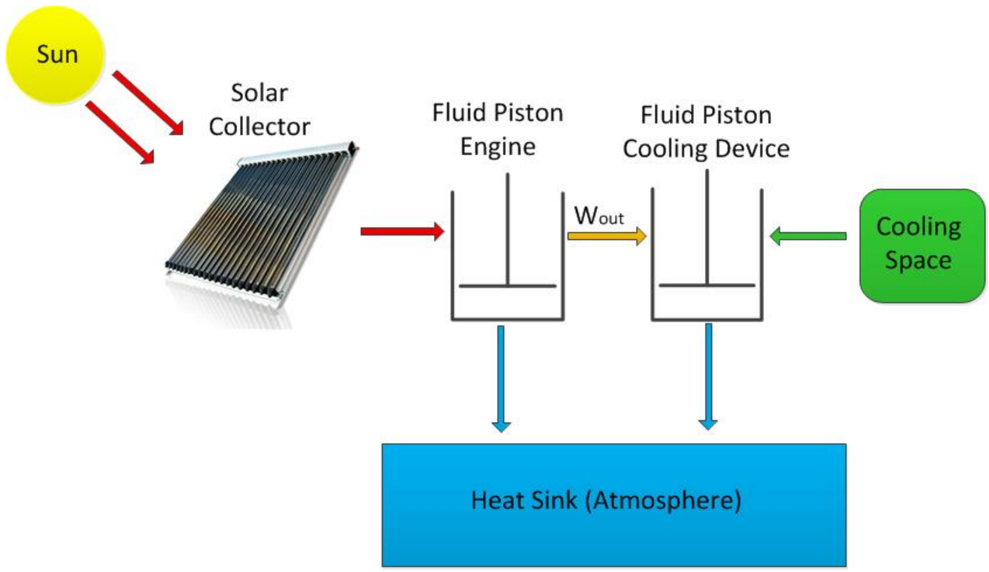

Figure 1: The concept of the solar cooling system.

Physical and Mathematical Model

Figure 2 shows a schematic diagram of the test rig with solar cooling system. It consists of two parts: engine and cooling machine parts. The engine part is made of the solar evacuated tube collector to heat water in the cylindrical evaporator and fluid piston engine. The evaporator is connected to the engine through the condenser. Steam produced by the solar collector drives the fluid piston engine. The fluid piston engine is made of two enclosed concentric plastic cylinders connected to each other in their bottom sections. The internal and external fluid columns act as a piston and fly wheel, respectively. The system is self-starting and the frequency of oscillations is about 1.5-3 Hz depending on the air volume above the external liquid column in the engine. The fluid piston is activated by the thermal energy generated in the evaporator. The pressure variation of air in the space above the external water column of the engine also drives the fluid piston of the cooling machine which has a U-shape. The condenser and cooler are used to reject the heat from the cycle of the engine and cooling machine.

The engine part and its mathematical model are described in details by Mahkamov et al. in [13].

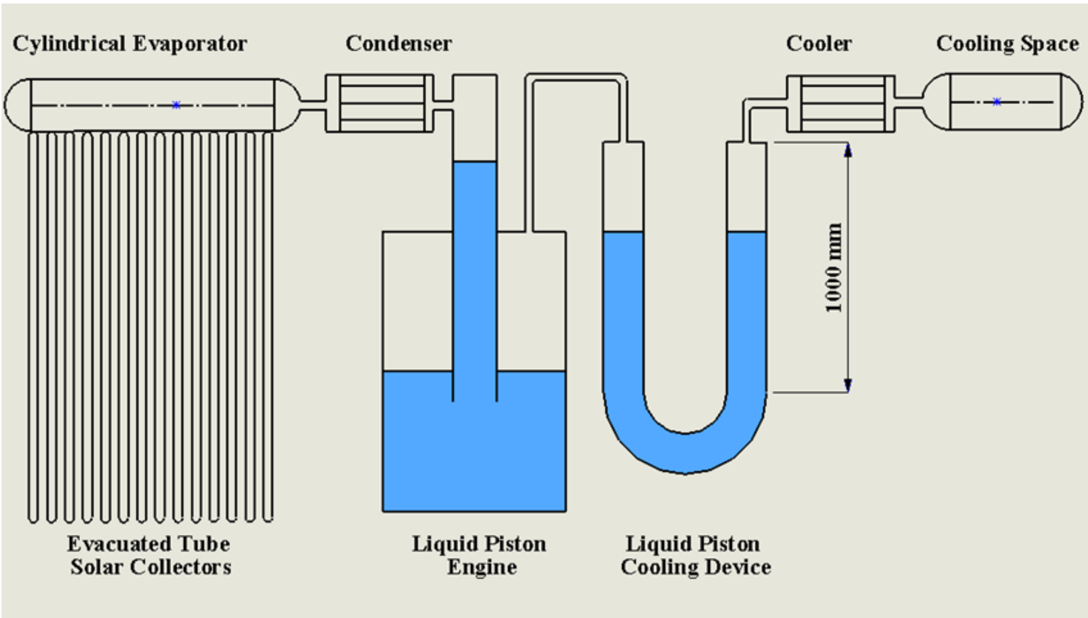

Figure 2: The fluid piston solar cooling system.

The calculation scheme for the mathematical modelling of the cooling part of the system is presented in Figure 3. It consists of three main control volumes, namely for fluid piston converter, cooler and cooling space. The working fluid in the system is air which is assumed to behave as an ideal gas. The pressure and temperature of the air in the system vary due to the change in the volume caused by oscillations of the fluid piston with the expansion and compression processes taking place in the cycle. The heat generated during the compression process is rejected in the cooler and the cooling effect generated in the cooling space during expansion process. The cold generated then can be transferred to the process heat carrier.

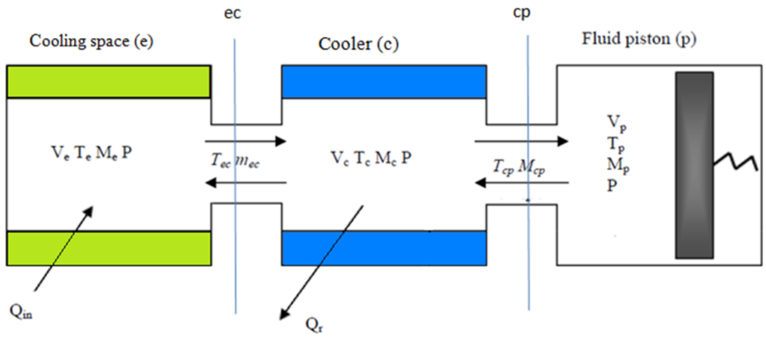

Figure 3: The calculation scheme of the cooling system.

The temperatures in the control volumes are affected by the direction of gas flow in interfaces between cooling space and cooler (denoted as ec) and cooler and fluid piston cylinder (shown as cp in Figure 3). For each of the control volumes mass and energy conservation equations are written.

The energy equation for the control volume can be presented as [14]:

$$\dot{Q} + (C_p \dot{m} T)_{in} - (C_p \dot{m} T)_{out} = P\frac{dV}{dt} + C_v \frac{d}{dt}(mT) \quad (1)$$

The displacement of the fluid piston is described as

$$X = X_0 \cos(\omega t) + L \quad (2)$$

where L is the starting position of the fluid piston.

The air pressure in the system is found by adding to each other energy equations (1) written for control volumes:

$$\frac{V_t}{\gamma - 1}\frac{dP}{dt} = -\dot{Q}_r - \frac{\gamma}{\gamma - 1} P \frac{dV_p}{dt} + Q_e \quad (3)$$

Here V_t is the total air volume in the system, Q_e are heat losses and $\dot{Q}_r$ is the heat rejected from the cooler, which calculated by applying the effectiveness-NTU method presented in [15].

MATLAB/Simulink environment

The above set of equations was solved in the MATLAB/Simulink environment. The developed Simulink model was built as a closed loop to simulate the proposed dynamic solar cooling system, as shown in Figure 4. After reaching the steady state condition, the variation in the fluid piston volume, the system air pressure and temperatures in every control volume are defined. The MATLAB/Simulink model also contains a set of criterion to establish whether the steady regime of operation is achieved during numerical integration. The heat losses in all three control volumes are calculated to produce more accurate results.

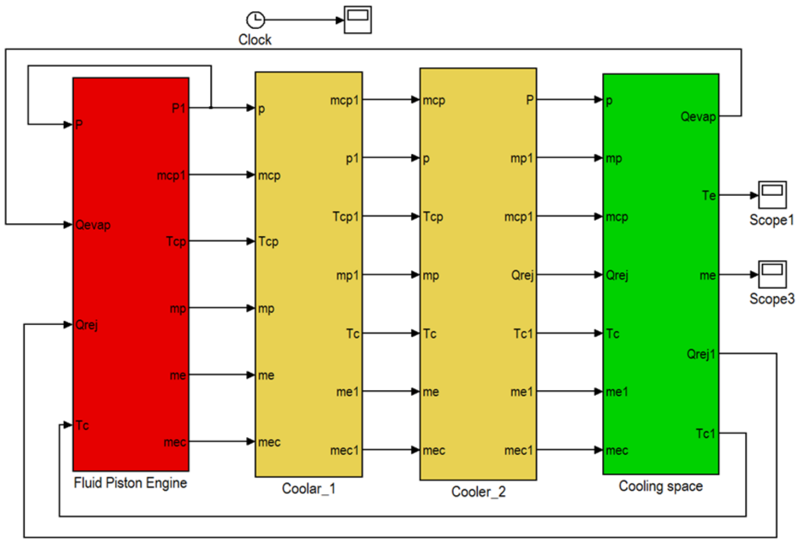

Figure 4: Simulink model of the solar cooling system.

Theoretical results

The operation of the cooling system was simulated for the specified amplitude of the fluid piston in the engine part and its frequency equal to 0.1 m and 3Hz, respectively. In addition, the temperature of the cooling water that enters the cooler was set to be 20° C. These conditions correspond to the operation of the fluid piston engine, tested experimentally in [11]. The displacement of the water column in cooling machine over the cycle is shown in Figure 5. Due to variation of the total volume of the cooling system the air pressure also periodically changes between 1.06 and 0.958 bar, see Figure 6.

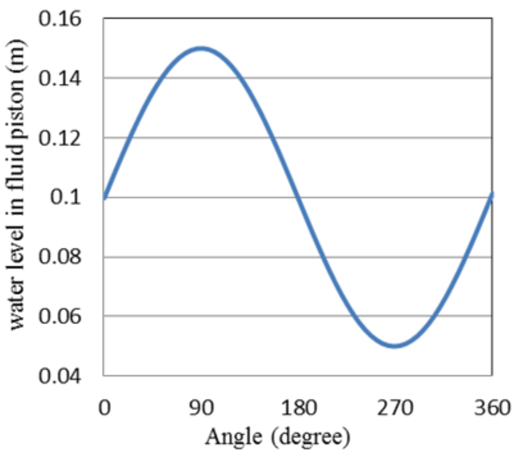

Figure 5: The liquid piston displacement.

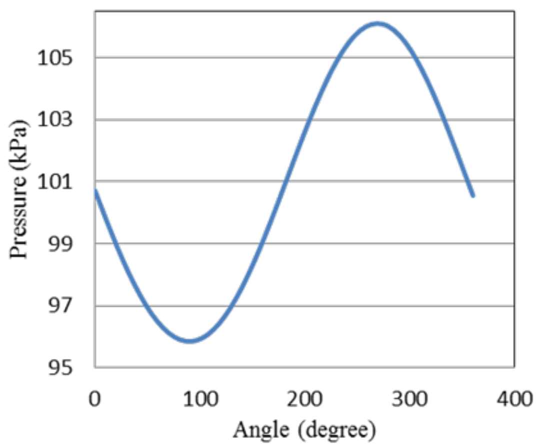

Figure 6: Air pressure variations.

Figures 7 and 8 demonstrate the variations of the temperature of air in the cylinder and cooling space, respectively. It can be seen in Figure 7 that the amplitude of the temperature variation in the cylinder is 15 degrees with maximum and minimum temperatures being 304 and 289 K. The range of the temperature variations in the cooling space are about 22 degrees with maximum and minimum temperatures being 303 and 281 K, respectively.

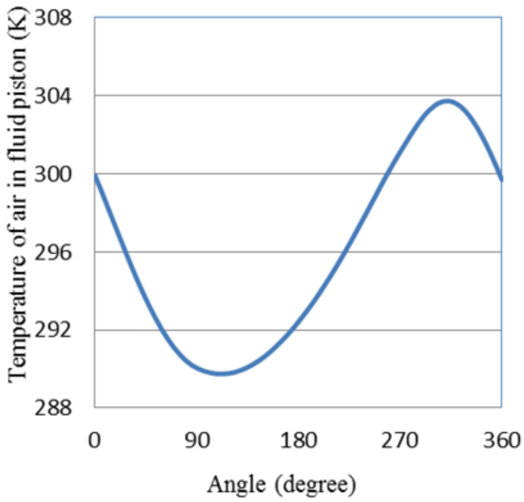

Figure 7: Air temperature in the cylinder.

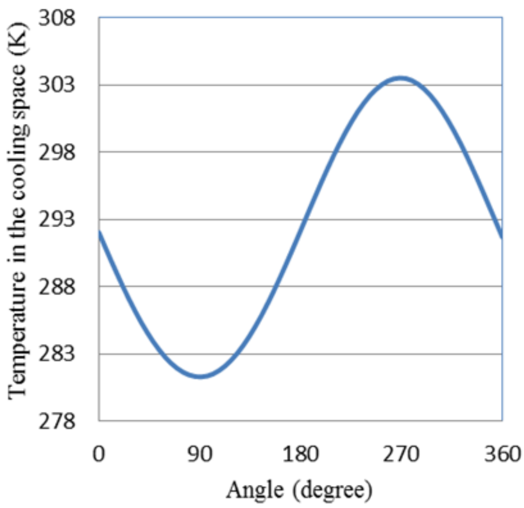

Figure 8: Air temperature in cooling space.

Experimental test rig

The engine test rig consists of the engine part with condenser, U-shaped cooling machine with cooler and heat pipe evacuated-tube solar collectors with the solar radiation simulator, see Figure 9

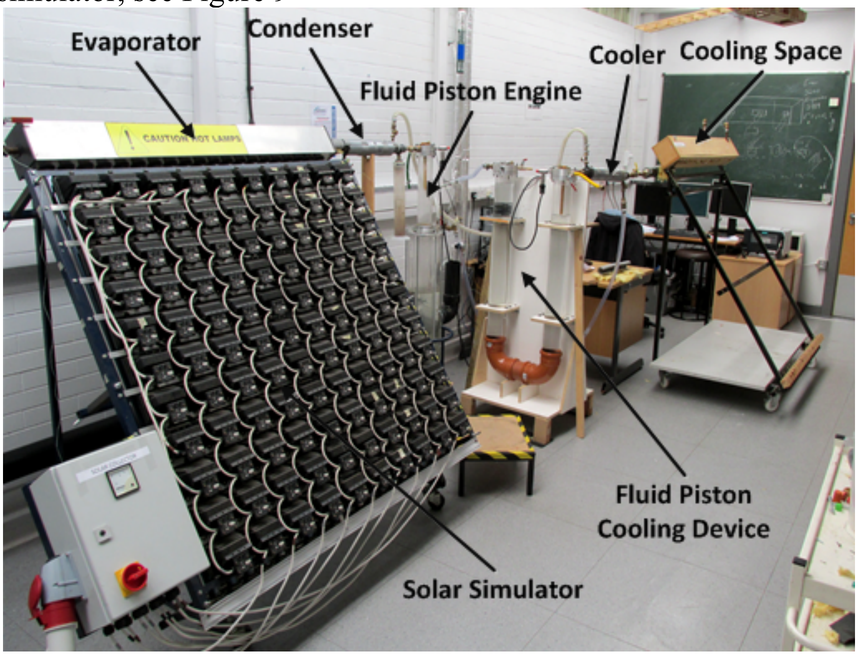

Figure 9: The test rig.

The evaporator is also the upper manifold of the solar collector which houses heads of heat pipes of the evacuated tube solar receivers. In this manifold the heat from head of heat pipes is transferred to the water and it is boiled producing steam. Generated steam is turned into the liquid in the condenser and returned back to the manifold. The pressure rise in the manifold initiates oscillations of water column (fluid piston) in the engine part. The solar simulator is made of 110 tungsten halogen lamps (150 W each) controlled by 3-phase variable transformer. The heat flux form halogen lamps onto the surface of the evacuated tubes was measured using a PMA 2200 photometer as a function of the 3-phas transformer voltage. The changes in the temperatures, pressures and levels of water columns were recorded using National Instruments DAQ, as shown in Figure 10. The types and specifications of sensors together with their locations are presented in Table 1.

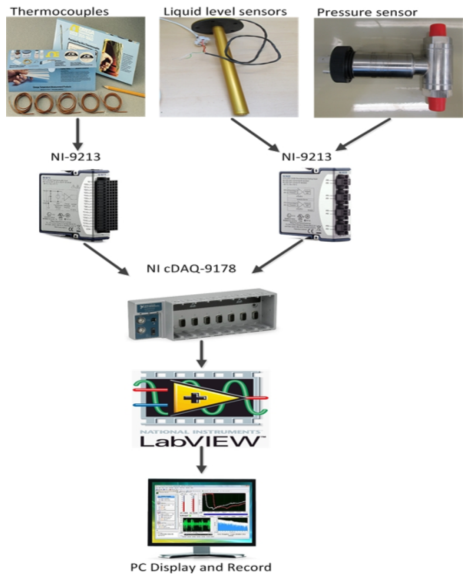

Figure 10: Data acquisition system.

Table 1: Specifications of the different sensors.

Component	**Sensors**	**Description**
Fluid piston engine	Water column level; Pressure; Temperature.	Level sensor: The aluminium R-series liquid level sensor by Gill Sensors (UK) with sampling rate of 80Hz. Pressure sensor: UNIK 5000 differential pressure transducer (-4 to +4 bar gauge), Druck Ltd Temperature sensor: The PFA insulated T-type thermocouples with thickness of 0.08mm.
U-Tube liquid piston cooling machine	Water column level; Pressure; Temperature.	
Cooling space	Temperature	

Experimental Results

The experimental results on oscillations fluid pistons in engine and cooling machine, cyclic variation in the air pressure and temperatures in the cylinders and cooling space are presented in Figures 11-15. It can be seen in Figures 11 and 12 that the amplitude of the fluid piston engine is about 5 cm whilst in the cooling machine this value is 1.6

cm. This difference is due to difference in diameters of plastic pipes used to make the engine and cooling machine (8.5 and 10 cm, respectively) frictional losses in the movement of the water columns in the internal and external cylinders of the fluid piston engine and the cylinder of the cooling machine. The changes in the air pressure in the engine and cooling parts over the cycle are shown in Figure 13.

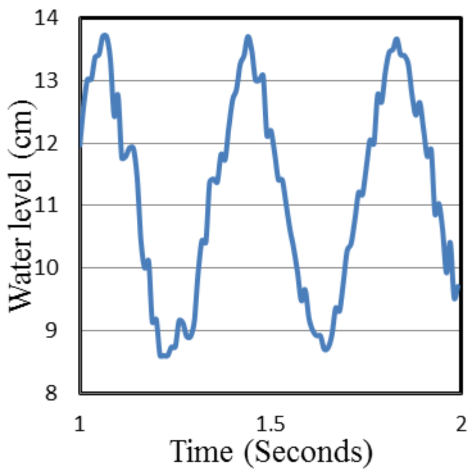

Figure 11: The engine liquid piston displacement.

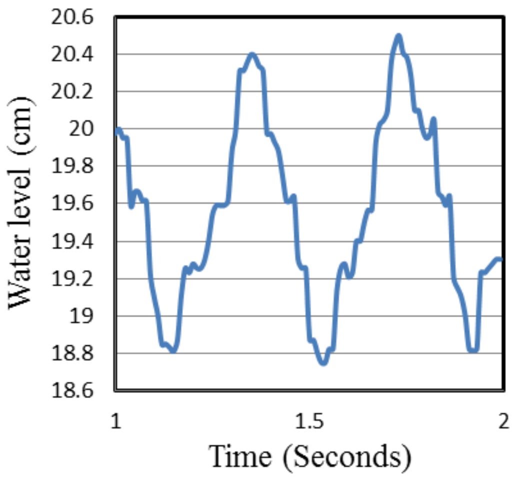

Figure 12: The cooling machine liquid piston

displacement.

Before switching on the solar simulator, the air gage pressure in both the engine part and cooling part are set to be equal to the atmospheric pressure. By switching the set The oscillation of the air pressure and cooling parts is between 0.032 and -0.073 bar (gage) in the engine part and between 0.11 and 0.02 bar (gage) in the cooling machine.

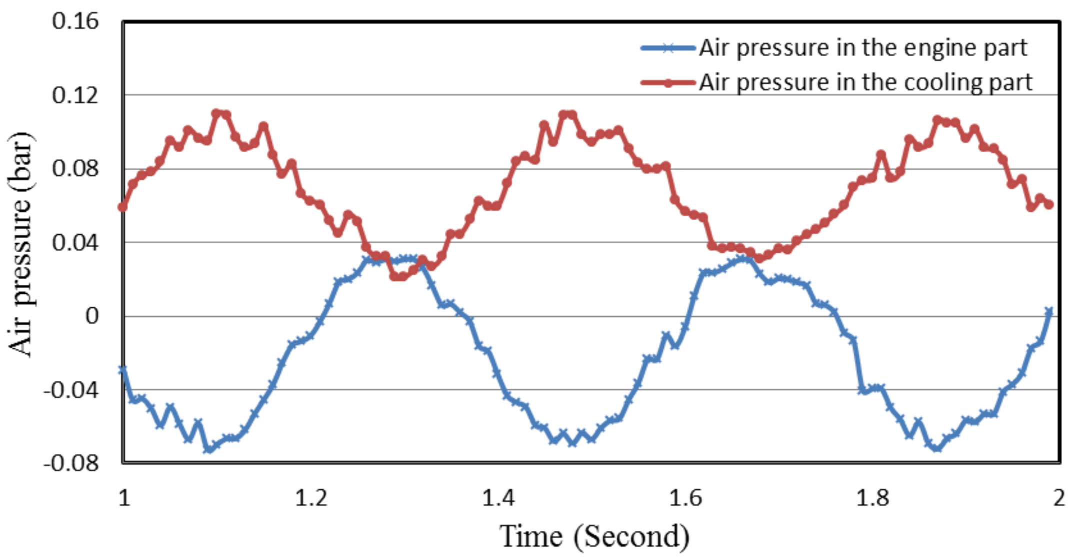

Figure 13: Air pressure in the engine part and cooling part.

Figures 14 and 15 show the variation in the air temperature in the cylinder of the cooling machine and in the cooling space. It can be seen that the average air temperature in the cylinder is 294.24 °K and this value in the cooling space is 292.7 °K. This demonstrates that the cooling effect takes place in the system with a 1.54 degrees reduction in the temperature of air.

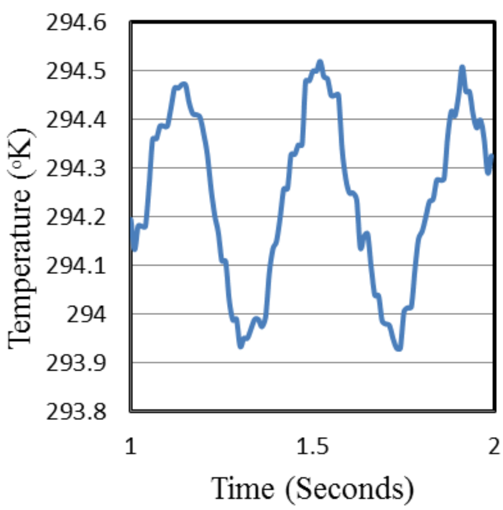

Figure 14: Air temperature in the cylinder of cooling machine.

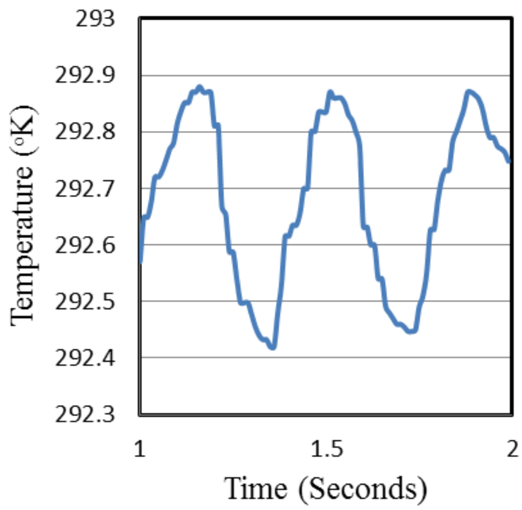

Figure 15: Air temperature in the cooling space.

Conclusions

In this study, the concept of the solar cooling system based on fluid piston converters is presented. The mathematical model of this cooling system was and numerical simulations were performed in MATLAB/Simulink environment. The possibility of producing the cooling effect in the system was demonstrated by means of numerical simulations and experiment. The theoretical reduction in the air temperature was about 3 degrees whilst in the experiment this value was found to be 1.54 degrees. The deviation between the theoretical and experimental results is due to unaccounted heat losses in the system.

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