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Experimental test bench for studying the boiling dynamics

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Abstract. The need of reducing the fuel consumption and pollution in case of road vehicles force the researchers to find solutions. Since the improvements of the internal combustion engine by design are on a rather flat trend, the researchers are looking to recover the lost energy. About 70% of the fuel's potential energy is released into the atmosphere as heat. This energy can be recovered in different manners like Rankine cycle, thermoelectric Peltier modules, absorption refrigerator cycle, and so on. The steam engine might be a promising candidate. Depending on the operating regime, the fuel economy can be up to 31.7%, accordingly to some re-ports from the open literature. The scope of the present research is to make an experimental research on a steam engine where the boiling takes place directly in the engine cylinder. So the preliminary investigations are required for this purpose. As a first stage, an experimental test bench for studying the vaporization in an enclosure is presented in the paper. The experimental test bench will be equipped with a controllable heat source at adjustable volume and a complete automatization for process monitoring and control.

1. Introduction

The energy recovery in case of the internal combustion engine is one of the possibilities to improve the global efficiency of it. Therefore, it is proposed for study a steam engine at which the boiling will take place directly within the cylinder eliminating in this way, the boiler which is an additional system to care of and also dangerous in some situations. For the proposed engine, the liquid water would be sprayed on an in-cylinder hot wall. The vaporization will take place leading to a pressure increase and finally to the piston movement. Of course, the efficiency would be rather small if the vapor does not superheat meanwhile. For doing a feasibility study of such an engine, it is important to know how the vaporization takes place in a closed container, where the pressure will be not constant due to vaporization and increase in vapor amount.

The vast majority of research that is somewhat connected to the proposed topic relates to spray cooling. In this studies, the pressure at which the process takes place is kept constant and also there is a continuous spraying.

Liang and Mudawar [1] have done a review of the spray cooling and they pointed out the influence of different parameters on the spray cooling process and vaporization regime. Mudawar and Estes [2] developed a correlation for predicting the critical heat flux (CHF) for different nozzles flow rates and subcooling. They pointed out, that there is an optimum distance between the nozzle and the surface that maximizes CHF. Visaria and Mudawar [3] have also done a systematic study concerning the influence of different parameters like nozzle type, subcooling, flow rates, orientation on the CHF. Horacek et al. [4] concluded that the CHF is more influenced by the length of the contact line than the wetted area fraction. During this research, they pointed out the influence of the dissolved gas on the

CHF. Gilberto Moreno Jr [5] analyzed the influence of the heater type (coated, non-coated), the distance between the nozzles and heater, coolant type and subcooling on heat transfer characteristics. Matthias Winter [6] studied also the influence of the working fluid, subcooling, saturation conditions and the surface topography. Rui Zhao et al [7] presents a mathematical model for the spray cooling and several experimental results. The model end experiments include the vaporization effect but they are not focused on this aspect.

From of all these studies, we can conclude that there are many parameters that are influencing the vaporization process during the spray cooling. We will focus, for the beginning, on analyzing the influence of only a few parameters such as: the amount of liquid injected, the temperature of the heater, the subcooling, and the volume of the test cell, to determine the heat transfer coefficients required for the analysis of the operation of a steam engine with built-in boiler.

2. Test bench description

The experimental test bench used to determine the heat transfer coefficients and to analyze the boiling dynamics is depicted in Figure 1. The boiling process takes place within a cylinder closed at the bottom by a heater and at the top by a wall with an adjustable position. This solution, with an adjustable wall on the top, was chosen in order to make the experiments for different volumes of the cylinder. The bottom electrical plate heater is commercially available, mostly used for small boilers.

The heater is powered by a variable power supply to control the dissipated heat, and its temperature is monitored via two thermocouples. On the cylinder side, the water injector is mounted. The pressurized water is ensured from a reservoir through a sub-merged pump and liquid heater. The water pressure and temperature are monitored with the two sensors mounted in front of the injector. The steam exhaust is ensured through the exhaust pipe, controlled by an electromagnetic valve (steam valve). The wall and steam temperatures are monitored with thermocouples, and the pressure within the cell is monitored with a pressure sensor mounted on the cylinder side. For data acquisition and actuators control, NI data acquisition system is used together with a signal conditioning box. Data analysis and visualization are done using a desk-top PC and LabView software.

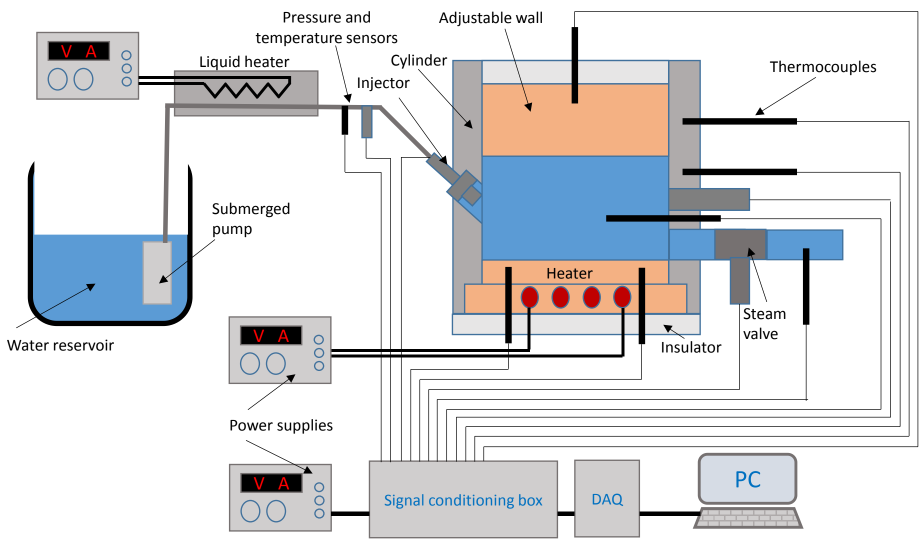

Figure 1. The proposed experimental test bench

3. Data analysis

The processes that take place within the cell are not steady state, therefore, the analysis of the time evolution of temperatures and pressures are not straightforward. The main goal of the presented experimental set-up is to determine the heat transfer coefficients between the liquid-wall, liquid-vapour and vapour-wall, to identify or estimate the injection law and to see if the proposed mathematical model can be suitable for analysing the functionality of a steam engine at which the boiling takes place directly in the cylinder.

The heat and mass transfer within the cylinder are schematically presented in Figure 2. As can be seen, two independent subsystems are considered, vapour and liquid respectively. Based on this arrangement a mathematical model was developed [8].

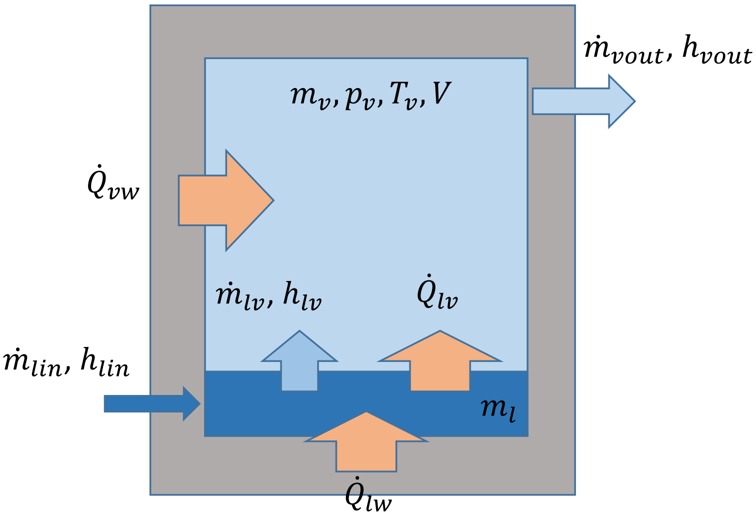

Figure 2. Schematic of the heat and mass fluxes trough experimental cell

After the injection takes place over the heater, a liquid film forms and it will re-ceive heat from the wall. The liquid temperature is computed based on the energy balance:

$$\alpha_{lw} \cdot A \cdot (T_l - T_w) + \dot{m}_{lin} \cdot h_{lin} - \dot{m}_{lv} \cdot h_{lv} = \frac{d(m_l \cdot c_{vl} \cdot T_l)}{dt} \quad (1)$$

where: T_l is the liquid temperature, T_w is the wall temperature, A is the liquid-wall contact area (heater area), α is the heat transfer coefficient, $\dot{m}_{lin} \cdot h_{lin}$ is the input water enthalpy, c_{vl} is the specific heat of water and m_l is the liquid mass within the cell.

When the liquid temperature achieves the boiling point, it will start to vaporize and the mass transfer is computed based on a simplified formula obtained from the Schrage's theory.

$$\dot{m}_{lv} \cdot \Delta H_v = \frac{1}{R} \cdot (T_l - T_{vs}) \quad (2)$$

Once the vaporization starts, the vapour mass within the cell will increase therefore the pressure will increase and leads to changes in the saturation temperature which can be computed with the Clausius-Clapeiron equation:

$$ln\left(\frac{p_v}{p_o}\right) = -\frac{\Delta H_v}{R} \cdot \left(\frac{1}{T_{vs}} - \frac{1}{T_0}\right) \quad (3)$$

where: p_v is the pressure of the vapour within the cylinder, p_o is a reference temperature, $\Delta H_v$is the latent heat of vaporization, R is the gas constant and T_o is the boiling temperature at pressure p_o.

Since there is a vapour incoming within the vapour system, for computing the pressure and temperature the first principle of thermodynamics for open systems, the equation of state and the mass conservation are used:

$$\dot{U} = \dot{Q} - \dot{W} + \sum \dot{m}_{in} \cdot h_{in} - \sum \dot{m}_{out} \cdot h_{out} \quad (4)$$

where the internal energy is:

$$\dot{U} = \frac{dU}{dt} = \frac{d(m \cdot c_v \cdot T)}{dt}, \tag{5}$$

the equation of state

$$p \cdot V = m \cdot R \cdot T, \tag{6}$$

and the mass conservation:

$$m_l = m_{in} - m_{lv} \tag{7}$$

$$m_v = m_{lv} - m_{vout}. \tag{8}$$

The water injection rate is calculated based on the following formula:

$$m_{in} = m_0 \cdot \left(1 - e^{-a \cdot \left(\frac{t - t_0}{\Delta t}\right)^{m+1}}\right) \tag{9}$$

where m_0 is the total injected mass, a and m are shape parameters, t is the current time, t_0 start of injection time, and Δt is the duration of the injection.

After the vaporization is complete and the pressure and temperature reach a constant level, the exhaust valve opens and the steam is removed from the test cell. Then a new experimental cycle resumes. This is repeated until the measured data repeats, indicating that at each start of the measurement cycle in the test cell either we have only gaseous water at atmospheric pressure or we always have the same mixture of gaseous water and air. It is indicated that the entire amount of air is completely removed from the test cell.

All the above equations have been implemented in a MatLab Simulink.

4. Results and discussions

Based on the presented model and the conditions presented in Table 1, some numerical results are presented.

Table 1. Parameters used for the calculations

Parameter	Value	Units
Test cell volume	2	l
Heating wall temperature	673	K
Injected liquid	6	g
Heat transfer coefficient (wall-vapour)	50	W/mK
Diameter of the cell	0.12	m

In Figure 3 the evolution of the liquid and vapour phase is presented. The liquid mass achieves its maximum value at about 26.8 seconds and the values are much smaller than the injected one which is 6g. This is happening because during the injection the injected water starts immediately to vaporize as can be seen in Figure 3, the vapour mass starts to increase once the injection starts.

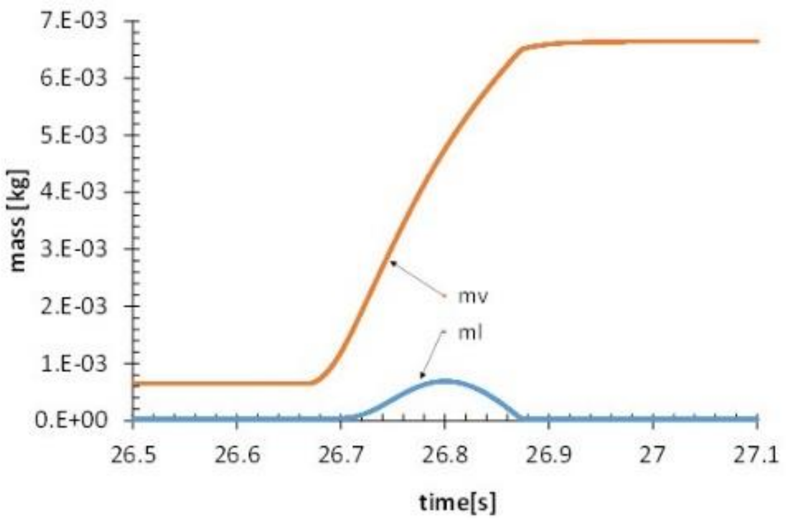

Figure 3. Liquid and vapour masses within the cell. The injection starts at 26.66 seconds

The scope of the presented model and the proposed experiments is to determine, in dynamic conditions, the heat transfer coefficients for wall-liquid, wall-vapour and liquid-vapour contact surfaces. The wall liquid heat transfer coefficient can be estimated based on the pressure variation within the cell, during the vaporization process. A higher heat transfer coefficient will lead to a faster vaporization and a faster change of the vapour pressure Figure 4. As can be seen in Figure 5, the change in temperature is rather small and cannot be used to get some useful information.

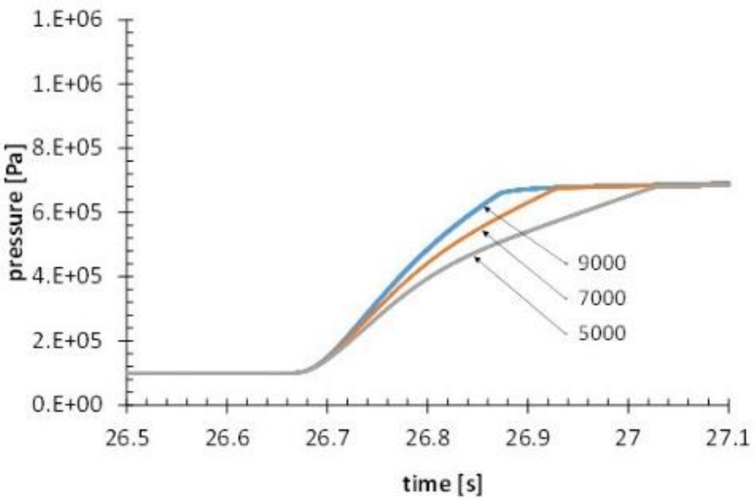

Figure 4. Pressure evolution within the cell for different heat transfer coefficients between the heating wall and the liquid phase

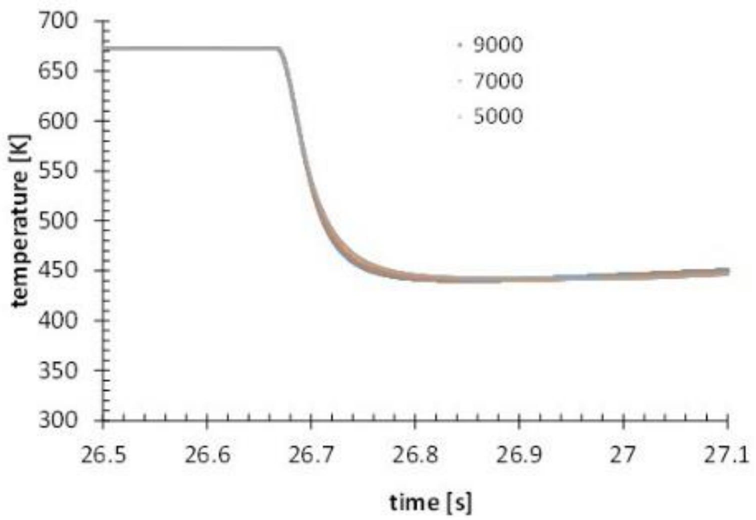

Figure 5. Temperature evolution within the cell for different heat transfer coefficients between the heating wall and the liquid phase

The pressure and temperatures are similar at the end of the vaporization process, regardless the heat transfer coefficient between the wall and liquid. Besides, the evolution is influenced by the wall-vapor heat transfer coefficients and adsorbed liquid film and vapor. From Figure 6 and 7, it can be seen that a higher liquid-vapor heat transfer coefficient leads to a faster change in pressure and temperature, although, after a long enough time, the values are going to be similar.

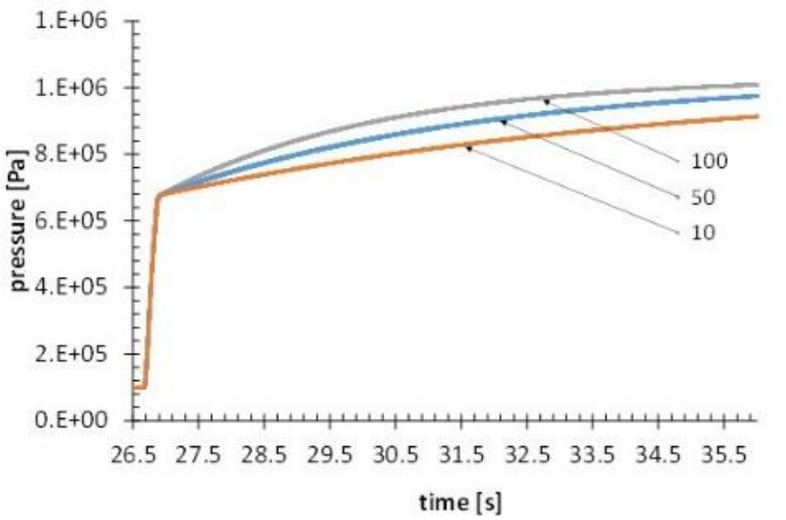

Figure 6. Pressure evolution within the cell for different heat transfer coefficient between the liquid and vapour phases

Some other parameters can be changed (test cell volume, heating wall temperature, the quantity of the injected water, the temperature of the injected water and so on) in order to obtain the complete set of unknown parameters.

The final goal of the experiment is to see if such a simplified model can describe well enough the processes that take place within the experimental cell and to use it for designing a steam engine where the boiling takes place directly within the cylinder.

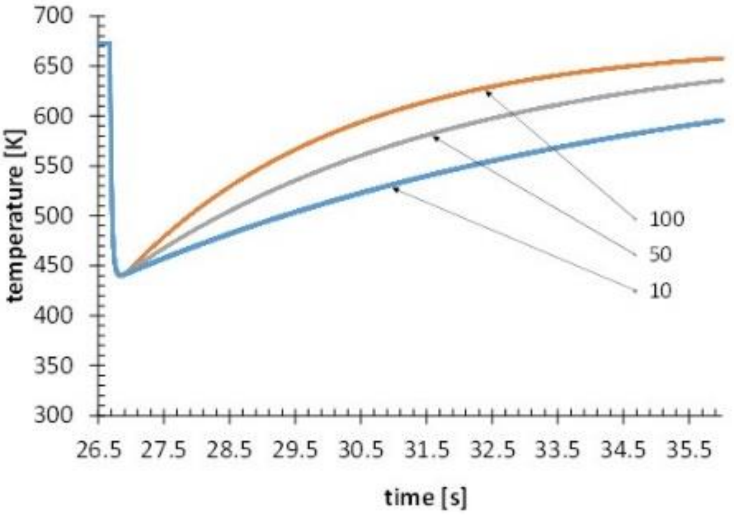

Figure 7. Pressure and temperature evolution within the cell for different heat transfer coefficient between the liquid and vapour phases

5. Conclusions

The experimental test bench and a simplified mathematical model for vaporization data analysis are presented in the paper. The experimental test bench has been designed in order to allow analysis of different parameters like the test cell volume, the quantity of the injected mass, the heat dissipated by the heater and the temperature and pressure of the injected liquid.

The simplified mathematical model used to describe the behavior of the temperature and pressure inside the test cell revealed that the evolution of these parameters is influenced by heat transfer coefficients (wall-liquid, wall-vapor, liquid-vapor). The final goal is to estimate these heat transfer coefficients by correlating the experimental results with the numerical ones.

Acknowledgment

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