ℙ periodica polytechnica

Mechanical Engineering
55/1 (2011) 43–47
doi: 10.3311/pp.me.2011-1.06
web: http://www.pp.bme.hu/me

RESEARCH ARTICLE

Experimental investigation of characteristics of cavitation in gasoline

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Received 2011-04-30

Abstract

Cavitation processes in gasoline were experimentally investigated with an objective of gathering measurement data for developing an appropriate numerical model with an intention of simulating flows in automotive fuel pumps. An experimental setup was manufactured to examine bubble growth and collapse processes in gasoline under different circumstances. Bubbles were found to collapse at only a considerably higher pressure than the one they were produced at resulting in a hysteresis in the bubble volume – absolute pressure diagram. According to the results a time-dependent deterministic model might be developed for the contraction phase in spite of nucleation being a stochastic phenomenon. Investigating the response of the system to small disturbances the experienced characteristics were very similar to those of heat conduction and diffusion equations leading to the conclusion that size changes of bubbles seem to be controlled by the heat and mass transport processes undergoing in their vicinity and the multicomponent diffusion effects can be responsible for the observed hysteresis. The experimental results established a good starting point for numerical model development.

Keywords

gasoline · cavitation · multicomponent diffusion · hysteresis

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1 Introduction

In automotive industry small side-channel pumps – the diameter of the impeller is approximately 30 - 40 mm – are used for fuel delivery. Expemimental and numerical investigation of such a fuel pump and a scaled model of it [1] [2] showed that during operation cavitation occurs which leads to the appearance of bubbles (Fig. 1). The total volume of these bubbles can be up to 30% of the flow field which all lead to the failure of fuel delivery especially at high temperatures. Some of these bubbles later disappear by absorption due to the increasing pressure in the fluid flow.

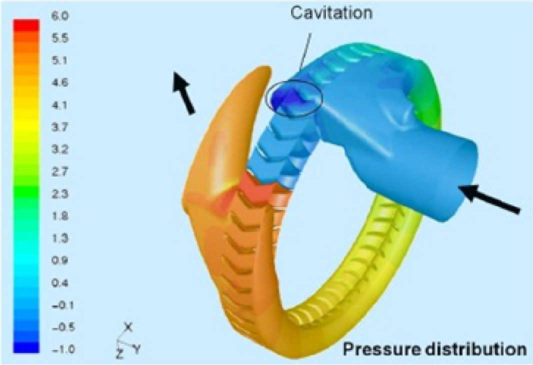

Fig. 1. Pressure distribution in a side-channel fuel pump [2].

The key point is that bubbles produced at a given absolute pressure were found to collapse only at significantly higher pressure (1 – 2 bars higher) resulting is a hysteresis in the bubble volume – absolute pressure diagram (Fig. 2). This phenomenon cannot be simulated by the existing models which do not consider fuel as a mixture of different components interacting with each other instead they work with averaged thermodynamic parameters. The multicomponent diffusion processes in the vicinity of the bubble-liquid interface are assumed to be responsible for the aforementioned hysteresis.

Modeling cavitation in various kinds of fuels has been a subject of major interest recently. The studies mostly focus on investigating cavitating flow in diesel injector nozzle hole in direct injection diesel engines as strong evidence has been provided by experimental studies [3–8] that the diesel spray characteris-

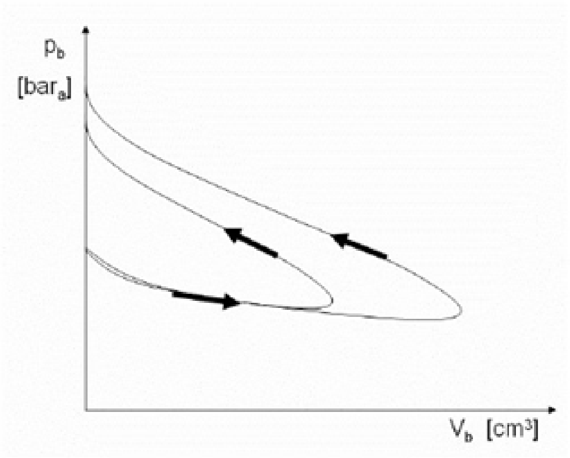

Fig. 2. Schematic diagram of the observed hysteresis in the pressure–bubble volume graph.

tics are heavily dependent on the nature of cavitating flow in the nozzle hole. These characteristics have a key role in combustion processes.

In such a nozzle the operating pressure is in the regime of 10-200 MPa [9] where pressure fluctuations in the order of magnitude of 1 bar do not play in important role therefore the results gained using the existing models are in fairly good agreement with those of the experiments. This is not the case considering the given fuel pumps. Under operating conditions the fuel pressure in these pumps ranges around 3–4 bars, consequently the applied cavitation models [10, 11] cannot provide a sufficient numerical simulation as they cannot describe and explain the hysteresis characteristics of cavitation bubble growth. Further models need to be developed which can simulate the aforementioned pressure variations making them applicable for simulation-based product development.

Since the literature does not provide sufficient experimental data to the authors knowledge, laboratory experiments had to be carried out aiming the investigation of bubble growth and collapse under different circumstances. These experiments provide several separate curves in the bubble volume-pressure diagram, which can help to identify the main characterestics of the phenomenon giving ideas about the physics in the background, and can also be used for validation of the future numerical models in which multicomponent diffusion is implemented.

2 Experimental setup

At this point experiments focus on the characteristics of cavitation therefore the simplest system, static fuel with controlled thermodynamic parameters is analyzed. The experimental setup was designed to be capable of creating a cavitation bubble the volume of which can be measured accurately while either the system pressure or the temperature is kept constant and the other parameter is varied in time. Fig. 3 shows the schematic diagram of the equipment designed to obtain the desired data.

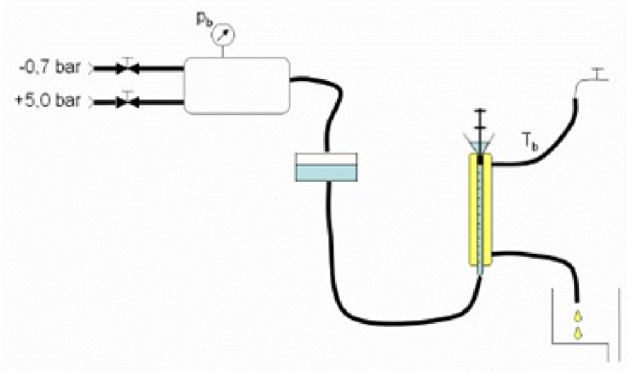

Fig. 3. Schematic diagram of the experimental setup.

A special glass device had been manufactured consisting of a measuring pipette, an adjustable closing plug and a water jacket for temperature control. The pipette has 0.05 cm^3 grading for measuring the bubble volume. The closing plug submerges into the liquid, and provides perfect sealing by an "O" ring and a fastening bolt. Controlled air pressure is introduced with a 200 cm^3 cylindrical glass tank with upper and lower portholes. Pressure is stabilized by using a 5 liter iron tank equipped with a pressure transducer. The pressure is measured with an accuracy of 0.1 mbar. Vertical distance between liquid levels in the cylindrical glass tank and in the pipette can be measured to obtain the corresponding hydrostatic pressure, taking the instantaneous bubble size also into account. The vertical position of the cylindrical glass tank can be adjusted within a range of ±2 m with respect to that of the pipette, in order to assist the filling process and to fine-tune positive or negative gauge pressures at the bubble. A standard pneumatic supply unit is used as positive pressure source. Negative pressure can be generated by a modified manual air pump, providing a reliable control over the bubble size.

Due to experienced unexpected temperature fluctuations of the municipal warm water supply originally used for setting the temperature, a high accuracy ($\pm 0.1^o$C) thermostat device was installed subsequently. It is important that only one bubble grows inside the system otherwise it is impossible to gain exact volume – time data. Therefore temperatures lower than the room temperature were avoided in order to prevent formation of disturbing secondary bubbles outside the measurement volume because these bubbles could find their way up to the measurement pipette coalescing the analyzed bubble in this way ruining the measurement.

Commercial summer fuel (Shell 95) of density 741 kg/m^3 was used in the experiments. The experimental device has to be reloaded with virgin (unused) fuel before each measurement since the concentration of solute gases is modified during the process.

3 Experimental procedures and results

The experiments were recorded with a video camera in order to ensure that all the gauges could be read synchronously. The volume of the bubbles depend on time so as the pressure and the temperature, both of which can be controlled manually. Having amended the measurement system by the thermostat and video recording, all parameters of the phenomenon became measurable by satisfactory precision. Both the pressure and the temperature can be set giving the opportunity of investigating isobaric and isothermal bubble formation as well. According to the histories of the applied pressure and/or temperature excitation the following four main types of experiments were performed:

3.1 Isothermal formation and absorption of bubbles

Bubbles of different size had been created by decreasing the pressure, then they were absorbed by increasing the pressure again, keeping the temperature constant throughout the process (27°C). It has to be emphasized that the pressure was set manually introducing some uncertainty. The experimental setup should be improved later with an accurate pressure controlling system. The applied excitation is similar to the thermodynamic process occurring in the pump during cavitation. It is expected that bubbles produced at a given absolute pressure can collapse only at significantly higher pressure according to a former industrial work having been carried out by our Department in connection with petrol product pipelines. In addition, the larger the initial bubble is, the higher the pressure is which is necessary to make the bubbles disappear (Fig. 2).

The initial reduction of pressure triggers sudden appearance of bubbles with different sizes at approximately 540 –560 mbar absolute pressure. The initial size is not reproducible: on one hand, it depends on the actual and local state of the fluid in addition to the external conditions; on the other hand, it is a result of microscopic processes such as the density of active cavitation nuclei, which is a stochastic variable. In our measurement series the initial bubble size has been varied by decreasing the pressure to different lower values even after the initial bubble appeared. In this way collapsing phases with an initial bubble size between 0.3 and 90 cm^3 could be observed yielding a more detailed map in the pressure-bubble volume diagram.

Being the formation of bubbles a very fast process, only the compression phase is observable technically (i.e. the measurement points fall on the upper branches of the curves shown in Fig. 2) under gradually increased pressures. The measurement data are summarized in Fig. 4.

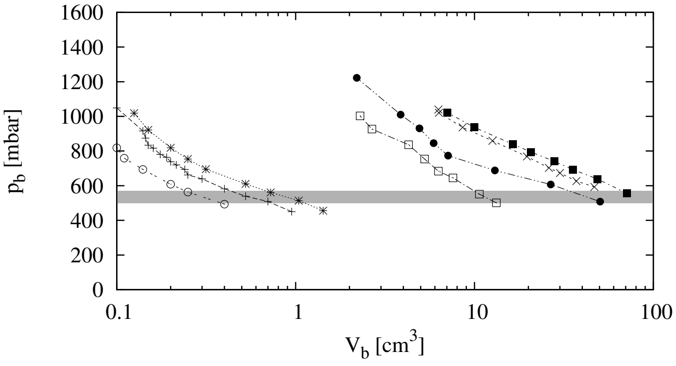

Fig. 4. Measurement data: isothermal formation and absorption of bubbles. Initial bubble formulation takes place in the grey-colour-marked pressure range.

The observed curves show a relatively linear connection between log V_b and p_b.

$$p_b = -p_0 \log V_b + p_1 \tag{1}$$

Fitting the obtained data with a linear functinn p_0 can be determined and it seems to be independent of the initial bubble size:$p_0 = 206.0 \pm 13.9$ mbar. This result suggests that the bubbles contract similarly to each other. This key finding can be illustrated if we plot the pressure values as a function of dimensionless volume where the actual volume values is divided by the maximum bubble volume during the process (Fig. 5). Thus it seems that the compression can be adequately modeled in a deterministic way.

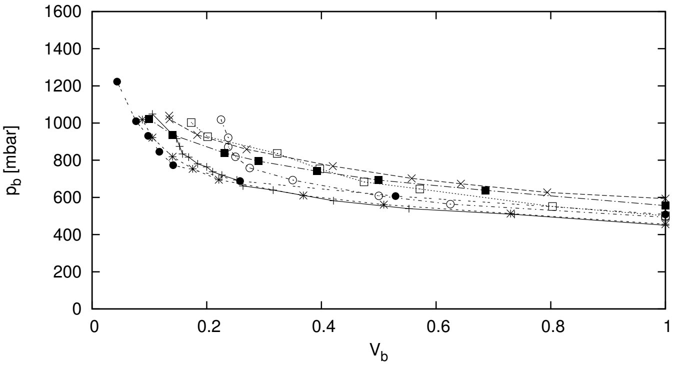

Fig. 5. Pressure as a function of dimensionless volume, non-dimensionalized by the maximum bubble-volume.

3.2 Bubble growth transients at constant temperature

A sudden pressure drop had been applied while keeping the temperature fixed bringing the liquid mixture into an oversaturated state. Therefore bubble formation was triggered. Maintaining the new value of pressure the volume of the growing bubble was recorded in time. It needs to be pointed out that the growth of the bubble slightly increased the hydrostatic pressure in the apparatus, therefore the constant pressure environment could only be realized approximately. The results are highly dependent on the initial conditions: pressure, temperature and initial bubble size. On Fig. 6 measurements refering to similar pressure and temperature are plotted. As we can see, the initial bubble size has a major effect on the characteristics of the process.

3.3 Isobaric bubble growth under varying temperature

In this case, the pressure was kept constant and the oversaturated state was reached by gradually rising the temperature. The indicated temperature values in Fig. 7 refer to the temperatures at which bubble formulation started maintaining the given pressure.

3.4 Bubble compression after isobaric bubble growth

In two cases the pressure was increased rapidly after a while from the original p_0 to a higher p_1 value maintaining the temperature to investigate the response of the system. As it can be

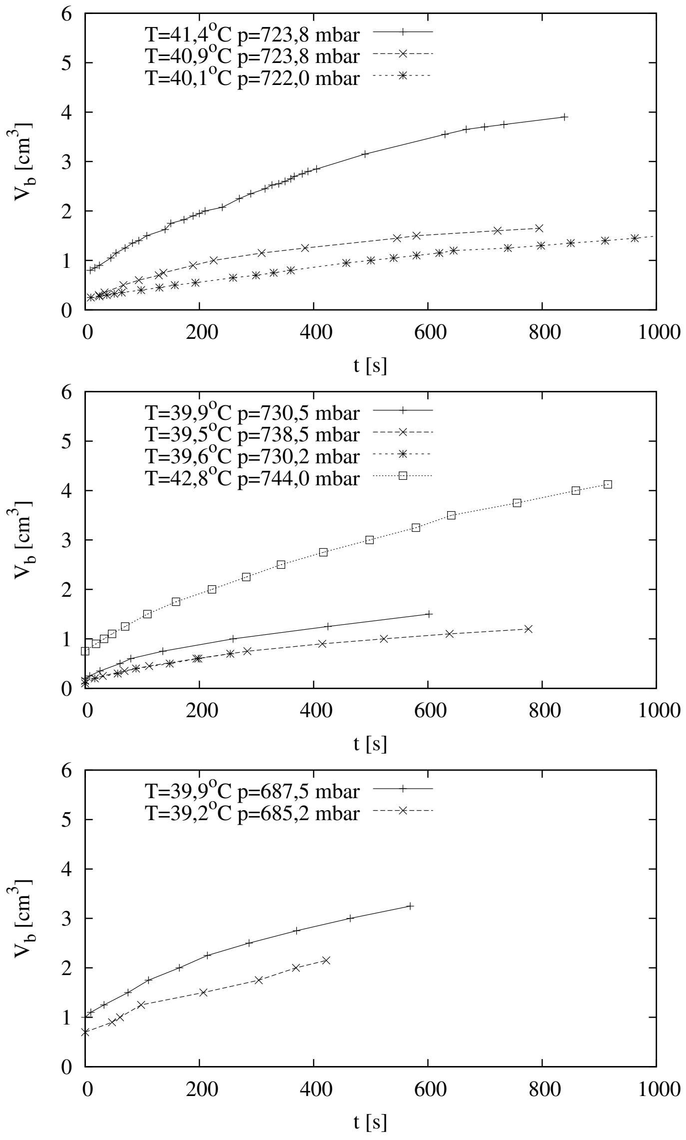

Fig. 6. Time dependence of bubble volume after a sudden pressure drop.

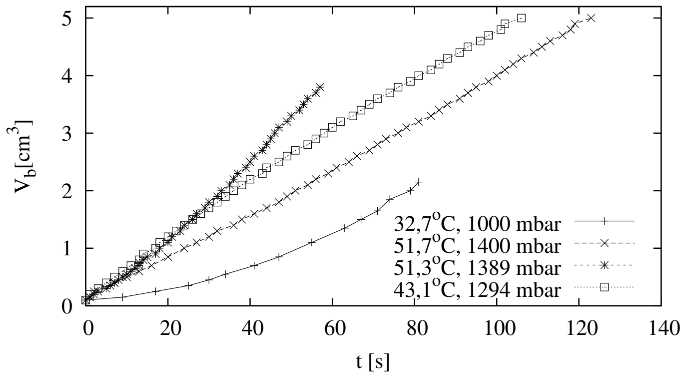

Fig. 7. Time dependence of bubble volume during isobaric bubble growth under varying temperature.

seen in Fig. 8 the bubbles do not collapse entirely instead the curves show saturation trends. It has been concluded that the system reacts by regularly decaying exponential responses to controlled external disturbances. This behavior is well known characteristics of heat conduction and diffusion equations.

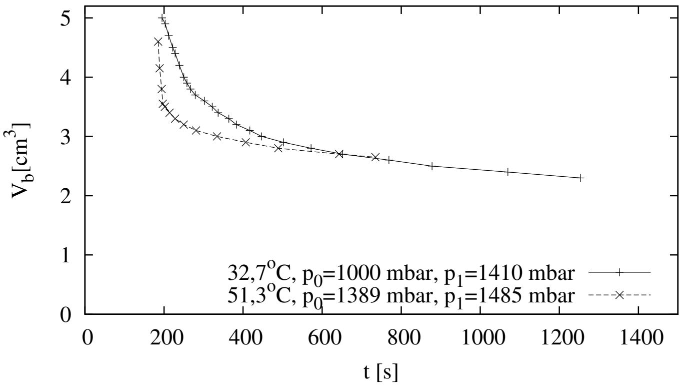

Fig. 8. Time dependence of bubble volume during compression due to the sudden increase of pressure after isobaric bubble growth.

4 Conclusions

Different measurement series were carried out in order to gain valuable data about the growth and collapse of bubbles in gasoline. The investigation aims to provide experimental results for developing cavitation models which are capable of properly simulating fuel flow in fuel pumps.

By investigating the isothermal bubble formulation it was shown that the nucleation cannot be considered as a deterministic process. It seems very likely that some kind of stochastic model will be necessary in the numerical simulation. According to the collapsing curves representing the contraction, for the development of existing bubbles a deterministic, time-dependent model might be developed.

In series *B* and *C* the time-dependence of bubbles have been observed and the quantitative measurements have yielded data for the first appearance of bubbles, which can be used to approximate the so called bubble line on the pressure vs. temperature phase diagram – also known as saturation curve - which signifies the beginning of phase transition in the given material. Knowing the bubble line is of key importance for the cavitation model.

According to the experienced response of the system to disturbances it was found that the characteristics were very similar to the ones of heat conduction and diffusion equations. This result seems to justify that the size changes of bubbles are controlled by the heat and mass transport processes undergoing in their vicinity and the multicomponent diffusion effects can be responsible for the observed hysteresis. These effects have to be modeled both theoretically and numerically in the future to be able to improve the presently available models.

Acknowledgement

This work is connected to the scientific program of the“Development of quality oriented and harmonized R+D+I strategy and functional model at BME” project. This project is supported by the New Széchenyi Plan (Project ID: TÁMOP-4.2.1/B-09/1/KMR-2010-0002). The paper has been supported by the Hungarian National Fund for Science and Research under contract No. OTKA K81621. The authors wish to acknowledge the help of Patrícia Arányi in data collection.

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