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Parametric Analysis for a Single Collapsing Bubble

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Abstract This work presents a sensitivity analysis for cavitation processes, studying in detail the effect of various model parameters on the bubble collapse. A complete model (Hauke et al. Phys Rev E 75:1–14, 2007) is used to obtain how different parameters influence the collapse in SBSL experiments, providing some clues on how to enhance the bubble implosion in real systems. The initial bubble radius, the frequency and the amplitude of the pressure wave are the most important parameters determining under which conditions cavitation occurs. The range of bubble sizes inducing strong implosions for different frequencies is computed; the initial radius is the most important parameter characterized the intensity of the cavitation processes. However, other parameters like the gas and liquid conductivity or the liquid viscosity can have an important effect under certain conditions. It is shown that mass transfer processes play an important role in order to correctly predict the trends related with the effect of the liquid temperature, which translates into the bubble dynamics. Moreover, under some particular circumstances, evaporation can be encountered during the bubble collapse; this can be profitably exploited in order to feed reactants when the most extreme conditions inside the bubbles are reached. Thus, this paper aims at providing a global assessment of the effect of the different parameters on the entire cycle of a single cavitating spherical bubble immersed in an ultrasonic field.

Keywords Cavitation · Single bubble dynamics · Parametric analysis · Sensitivity

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1 Introduction

Cavitation processes have been investigated over the last 90 years. The high temperatures and pressures reached inside the bubbles, together with the liquid pressure waves and the high velocity micro-jets generated due to asymmetric bubble implosions, have raised a great interest in possible industrial applications. In fact, since 1927 [17, 22], a wide variety of devices have been designed in different fields, such as organic and inorganic compounds synthesis and degradation [3, 11], polymerization reactions, electro-chemical reactions, medicine or material cleaning techniques, showing the potential of cavitation [14]. However, even though great advances have been achieved in recent years, the performance is still far from the optimum and intense studies are being conducted at present.

The high temperatures and pressures inside the collapsed bubbles (with radii between 4 and 60 microns) last for extremely short times (between 10^{-6} and 10^{-4} s) making very difficult to measure the variables inside the bubbles. It is then compulsory to resort to numerical simulation techniques in trying to understand the processes and improve the real system performance. Numerical techniques have been used during the last two decades as the main tool to scrutinize this phenomenon. The capability of numerical prediction is shown as the key factor to reduce experimental blind testing and to design indirect measurement techniques. All these studies are therefore aimed at minimizing the high degree of uncertainty limiting the potential applications of cavitation. The lack of a profound knowledge about the physics, the chemistry and the dynamics of this phenomenon prevents its rational exploitation.

This paper presents a parametric analysis allowing a better understanding of the cavitation phenomenon, predicting trends of the system response for external parameter changes. Variable properties related to the gas, the liquid and the driving pressure wave are analyzed separately.

The model output variables chosen as indicators of the bubble behavior are:

- The compression ratio, defined as the ratio between the minimum bubble radius attained during the implosion, R_{min}, and the equilibrium bubble radius, R_0.
- The peak pressure and temperature at the bubble center.
- The peak temperature at the interface, T_{int}, which provides information related with possible reactions which might take place in the liquid surrounding the bubble.
- For some particular situations, the evaporation flux, J, and the water mass fraction, $Y(H_2O)$, will be also shown.

Finally, in some cases the temporal evolutions of some parameters will be shown as a function of the dimensionless time $t' = tf$.

2 Characteristic Stages

One of the most important steps in order to understand cavitation is to distinguish and unveil every one of the different characteristic stages into which the process can be divided. A description of the typical stages have been already described in [8]. However, from the results obtained using the complete model by Hauke et al. [6], the compression stage can be further subdivided into two stages, which are believed to help in understanding the effects of some of the process variables. The proposed stages are:

Expansion stage. During this stage the liquid pressure decreases and the bubble expands acquiring some kinetic energy. This energy is related to the bubble growth following the liquid pressure. Small bubbles can easily follow the driving pressure because the kinetic energy set in motion is small. When they are larger than a critical size, the bubble characteristic response time is larger than the external wave characteristic time (f^{-1}). Under these circumstances, bubbles remain “frozen”.

Deceleration stage. As the external liquid driving pressure tends to rise, and given that the bubble and its surrounding liquid have a certain kinetic energy due to their outward motion, the bubble continues its expansion until it is stopped. During this stage, the bubble still expands and its pressure decreases, whereas the liquid pressure tends to increase.

Initial compression: Once the bubble growth stops, the pressure differences between the gas-liquid interface and the bulk liquid compresses the bubble. This pressure difference is a function of the bulk liquid pressure (that will depend on the ultrasonic wave amplitude) and the bubble pressure (which will be function of the expansion during the previous stage). When the bubble pressure is lower than the bulk liquid pressure it is accelerated inwardly. It will be essential to determine the time during which bubble is accelerated. Processes like mass and heat transfer have an influence on the bubble behavior during this stage and therefore, on the conditions reached during the collapse. Thus, using a complete model, the present work aims at clarifying the real effect of those variables influencing the heat and mass transfer across the interface.

Implosion: When high inward velocities are reached, the surrounding liquid kinetic energy is large. Therefore, when the bubble pressure is higher than the pressure in the bulk liquid, the system (bubble + surrounding liquid) is still being compressed due mostly to the liquid inertia. The higher the velocity, the smaller the ratio R_{min}/R_0, which is a measure of the implosion intensity. If velocities are high enough, final temperatures and pressures can be really very high.

Rebounds, liquid wave generation: For cases in which violent implosion are produced, the pressure difference created between the bubble and the bulk liquid makes the bubble to undergo a series of rebounds until its pressure is balanced by that of the liquid.

3 Case Study

The case study, described in Table 1, is based on the response to a driving pressure wave of frequency f and amplitude ΔP of a single bubble in the reference state where T_{liq} is the liquid temperature far away from the bubble, P_{liq} the reference pressure of the system, around which the liquid pressure oscillates, P_{vap} the vapor pressure of

Table 1 Case study characteristic parameters

Parameter	Value
T_{liq}	295 K
P_{liq}	101300 Pa
P_{vap}	3000 Pa
μ_l	$8\ 10^{-4}$ kg/(m s)
ρ_l	1000 kg/m^3
c_l	1500 m/s
R_0	19.3μm
σ	0.06 N/m
f	22300 Hz
ΔP	100000 Pa

the liquid, μ_l the liquid viscosity, ρ_l the liquid density, c_l the liquid speed of sound, R_0 the initial bubble radius (or equilibrium bubble radius) and σ the surface tension.

The driving pressure is sinusoidal, as it is typically encountered in ultrasonic cavitation,

$$P_l(r = \infty, t) = P_{\text{liq}} + \Delta P \sin(2\pi f t) \tag{1}$$

where $P_l(r = \infty, t)$ is the liquid pressure far away from the bubble, P_{liq} the reference liquid pressure, ΔP the amplitude of the driving wave, f the frequency and t the time.

For this analysis, the vapor pressure has been imposed as the minimum allowed liquid pressure. Even though it is possible to sustain negative pressures in the liquid during the rarefaction stage, in real systems the liquid pressure cannot become negative due to the presence of others nuclei. Therefore, for real applications, the effective pressure wave imposed to the bubble is not going to take negative values.

The present analysis is based on a model [6] which solves the full Navier-Stokes equations (including the energy equation) inside and outside a single bubble assuming spherical symmetry. The model uses the Rayleigh–Plesset equation [16], modified to include the compressibility effects and mass transfer processes [12], to approximate the liquid continuity and momentum equations. This equation has been widely used by other authors to describe the liquid behavior [15, 18, 23, 27].

For the mass transfer modelling (MT), the Hertz-Knudsen-Langmuir formula [7, 13], derived from the kinetic theory of gases, is used:

$$J_{\text{H}_2\text{O}}^{\text{tot}} = \frac{\beta(p_{\text{sat}} - p_{\text{H}_2\text{O}})}{\sqrt{2\pi R^0 T_{\text{int}}}} \tag{2}$$

This equation provides the total flux across the interface as a function of an experimental accommodation coefficient, β. As there is a large uncertainty in relation with the values of β, results using a standard value of $\beta = 0.35$ [24] and also for $\beta = 0$ are included. Hence, the influence of the mass transfer can be assessed based on this model.

Note that along this analysis, some extreme values of the parameters may be used in order to get a complete vision of its influence on the simulations.

4 Effect of Bubble Radius and Frequency

When a bubble is placed in an spherical flask undergoing an ultrasonic field, the sinusoidal liquid pressure causes continuous expansion/compression bubble cycles. Depending on the bubble radius, R_0, and the wave frequency, f, resonance conditions can be achieved, producing intense bubble collapses. For this analysis, it is assumed that the mass flux of Argon across the interface is negligible. Thus, the initial radius can be considered as a free variable which will depend on the amount of Argon initially contained in the bubble. The existence of other species like oxygen or nitrogen, which can generate soluble compounds during the collapse, could determine equilibrium radius for a given experiment conditions and should be taken into account in order to understand the effect of these two variables [20].

Figures 1 and 2 depict the peak temperatures and pressures during the implosion as a function of bubble radius and frequency. The results have been obtained including mass transfer effects across the interface. As can be seen, these two parameters are crucial in order to determine the bubble sizes experiencing implosions of different intensities. Both, frequency and bubble radius, have a strong influence on the characteristic liquid and bubble times, t'_l and t'_b, which are proportional to $1/f$ and to R_0, respectively.

- If $t'_b << t'_l$, the bubbles are able to follow the driving pressure and no violent collapses are produced.
- If $t'_b >> t'_l$, the bubbles remain almost undisturbed by the liquid wave. These bubbles would implode violently if the pressure is maintained constantly high,

Fig. 1 Peak temperatures reached during the implosion as function of the bubble radius (in metres) and frequency (in Hz)

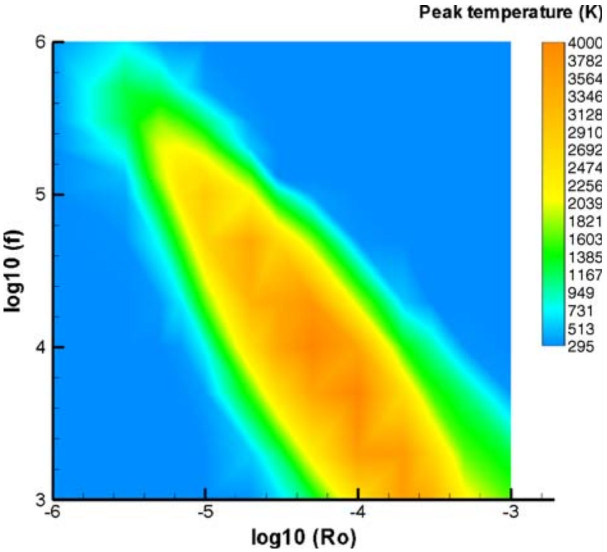
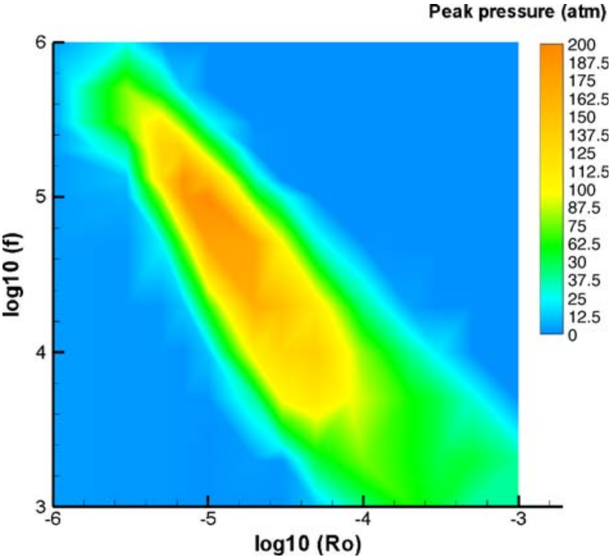


Fig. 2 Peak pressures reached during the implosion as function of the bubble radius (in metres) and frequency (in Hz)



like in hydrodynamic cavitation. It is also possible to make them implode if the second resonance frequency is achieved, appearing when the wave frequency is a multiple of the bubble natural resonance frequency. In this case, the wave amplitude of the induced pressure wave should be larger to produce intense implosions.

- It is when $t'_b \sim t'_l$ that the natural bubble frequency is equal to the frequency of the driving wave and high non-linearities appear resulting in intense implosions.

Regarding those bubbles that $t'_b \sim t'_l$, it is also remarkable that small bubbles tend to enhance the peak pressures during the collapse, whereas large bubbles tends to yield higher temperatures. The reason is that, when the collapse is produced and high velocities are reached, small bubbles evacuate more heat than large ones (due to the steeper temperature gradient inside the bubble). The higher heat transfer rate during the acceleration stage, the slower the bubble temperature and pressure increase, resulting in a longer acceleration stage and larger compression velocities. Finally, this is translated in a higher compression ratio and then, the peak pressure attained during the implosion is higher. For large bubbles, the temperature gradient is moderate, the acceleration stage tends to be more adiabatic and the pressure increase faster due to the density and temperature increment, consequently, this stage is shortened and the reached velocities are smaller.

Apart from other considerations (e.g., buoyancy forces or the interaction distance among bubbles), it can be concluded that for real liquids in which initial nuclei are very small (of the order of 10 μm), high frequencies are required to produce strong collapses (around 10^5Hz).

On the other hand, if frequencies are low, it may be necessary to generate large bubbles for their collapse in the high pressure zone to occur.

As a rough approximation, it is found that cavitation condition are achieved for those bubble whose characteristic velocity $v_0 = R_0 f$ is around 1m/s.

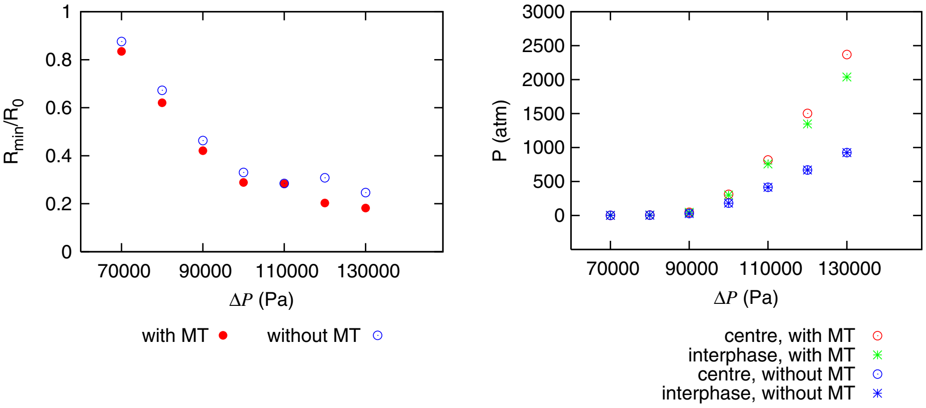


Fig. 3 Compression ratio vs. wave amplitude (*left*). Peak bubble pressure vs. wave amplitude. *MT* = Mass transfer

5 Liquid Pressure and Wave Amplitude Sensitivity Analysis

The influence of the driving pressure has been already studied in [19] for a wide range of conditions. Although the new model does not reveal significant changes in comparison with previous studies, the influence of this variable is included in this work in order to provide a complete overview of the effect of different variables on the process.

Implosions are influenced by the ratio $\Delta P/P_{\text{liq}}$. When the pressure wave amplitude is decreased, maintaining the liquid pressure constant, this ratio decreases and no extreme conditions are reached inside the bubble. Therefore, the amplitude of the driving pressure wave, ΔP, has a strong influence on the implosion intensity (see Figs. 3 and 4).

Fig. 4 Peak temperature at bubble center vs. wave amplitude

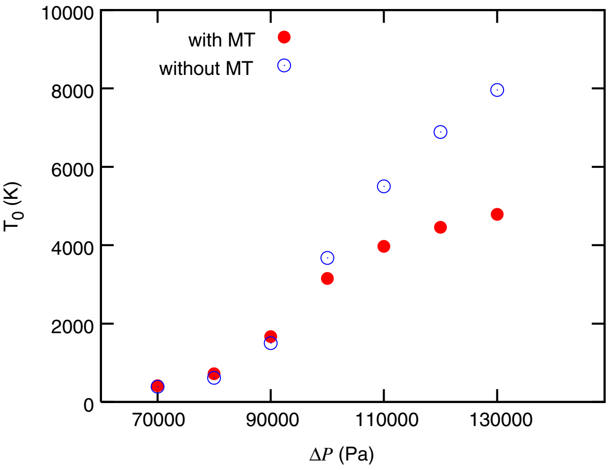
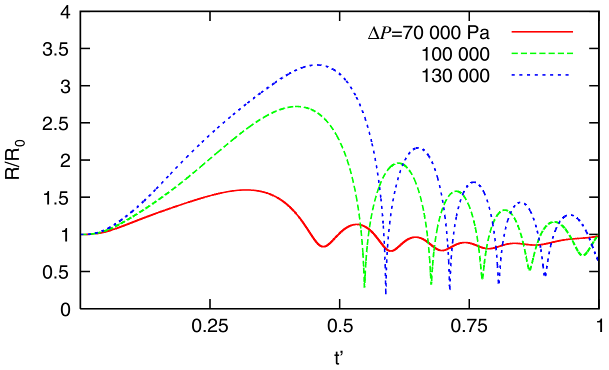


Fig. 5 Radius temporal evolution for three different pressure wave amplitudes



The larger the wave amplitude the more intense the implosion, as characterized by the peak temperatures and pressures. In fact, increasing the pressure wave amplitude enlarges the range of bubbles imploding violently. For very large wave amplitudes, the effect of the mass transfer causes the bubble temperature to decrease due to the increment of the water molecules inside the bubble [26].

When the wave amplitude is of the order of the reference pressure or even larger, the expansion is enhanced (Fig. 5) due to the increment of the pressure difference between inside and outside the bubble. As a result, high interface velocities are predicted and the inertia acquired by the surrounding liquid during the expansion increases. Thus, the beginning of the compression process is delayed and the pressure difference between the interface and the bulk of liquid increases; this finally translates into high compression velocities.

Changing the reference liquid pressure, P_{liq}, the ratio $\Delta P/P_{\mathrm{liq}}$ can be also controlled. Thus, working at high pressures, will imply that the amplitude of the induced waves should be larger in order to get intense implosions.

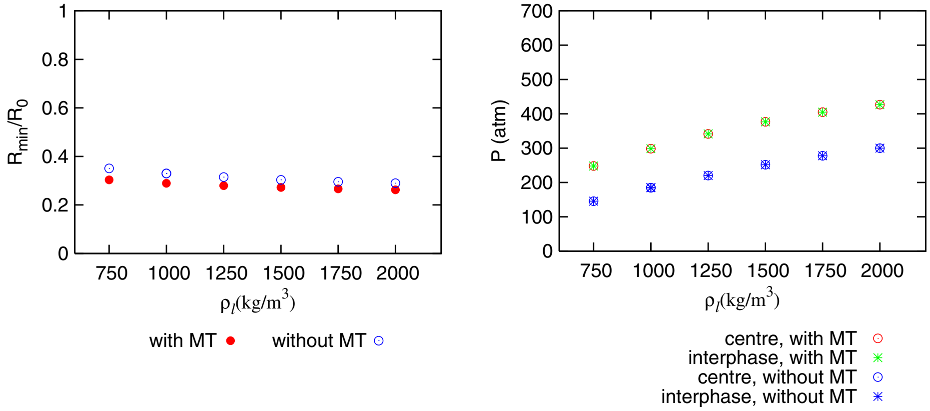
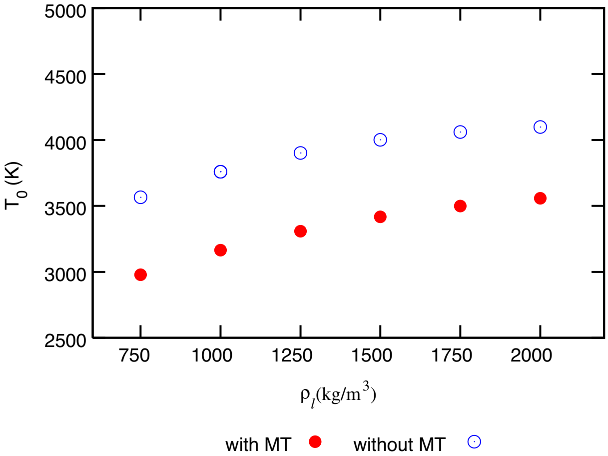


Fig. 6 Compression ratio vs. liquid density (*left*). Peak bubble pressure vs. liquid density (*right*)

Fig. 7 Peak temperature at bubble center vs. liquid density



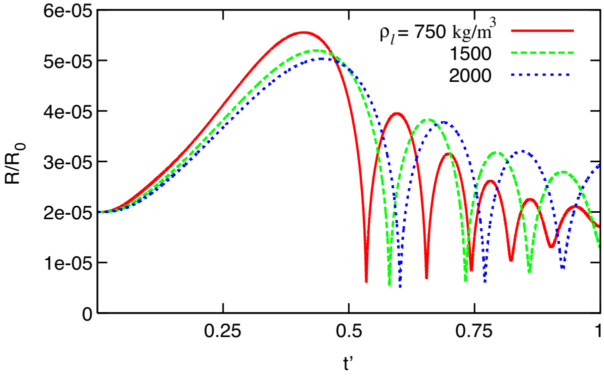
6 Liquid Density Sensitivity Analysis

An increment of the liquid density yields slightly more violent implosions (Figs. 6 and 7), although its relevance is not as important as that of previous parameters.

The liquid density influences the momentum and the kinetic energy acquired by the liquid when it is accelerated. During the expansion, the deceleration time increases because of the higher liquid inertia. As a consequence, the pressure difference between the interface and the bulk of liquid at the beginning of the compression stage increases and slightly higher compression velocities are achieved. Such high velocities are reached not only by the bubble, but also by the surrounding liquid. Like in the expansion stage, the liquid inertia, of the order of $\rho_l u_l^2$, increases; this being an important factor to determine the intensity of the implosion.

We would like to remark that the liquid momentum depends also on u_l^2, which can be also influenced by the liquid density. In fact, it must be noticed that it is more difficult to displace the liquid around the bubble. This phenomenon has a relevant effect during the expansion. For high liquid densities, a smaller maximum radius is

Fig. 8 Liquid density analysis. Radius temporal evolution



predicted during the expansion (Fig. 8) and, as the compression velocity depends on the level of expansion, the implosion violence diminishes.

The delay in the compression stage and the higher momentum acquired by the liquid overcome the smaller expansion ratio, resulting in a larger momentum of the liquid during the compression and, therefore, more violent implosions.

7 Liquid Temperature Sensitivity Analysis

The liquid temperature can be easily controlled in experiments and this is the reason why theoretical and laboratory studies have been focused on the understanding of the effect of this variable [1, 9, 21, 25].

Unlike the rest of the previously considered variables, the effect of the liquid temperature T_{liq} on the bubble dynamics is a function of the importance of the mass transfer during the process (determined by β). The effect of this variable using both models, with and without mass transfer, is depicted in Figs. 9 and 10.

When no mass transfer is taken into account, the most relevant effect is the variations of the liquid vapor pressure with the temperature. As this parameter is used as a lower bound for the liquid pressure, the effective part of the pressure wave is smaller for higher temperatures (when the vapor pressure is of the order of the reference pressure) and, thereby, weaker implosions are expected.

When mass transfer effects becomes important (due to large values of β), the predicted trends are completely different. Initially, the bubble temperature equals that of the liquid and, due to the fact that the pressure is the same in all cases, the higher the liquid temperature, the smaller the initial bubble density. As the initial density is smaller,the bubble offers less resistance to expansion, which finally translates into a larger growth. This is finally translated into a higher degree of expansion. Thus, for the case of water, when the liquid temperature is increased from

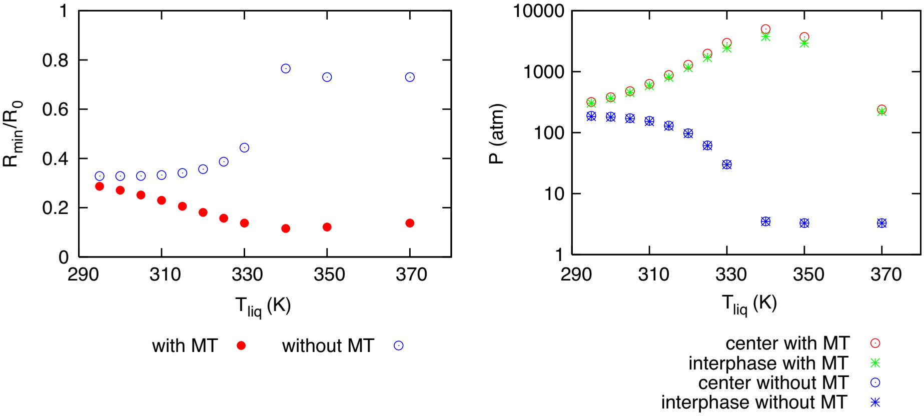
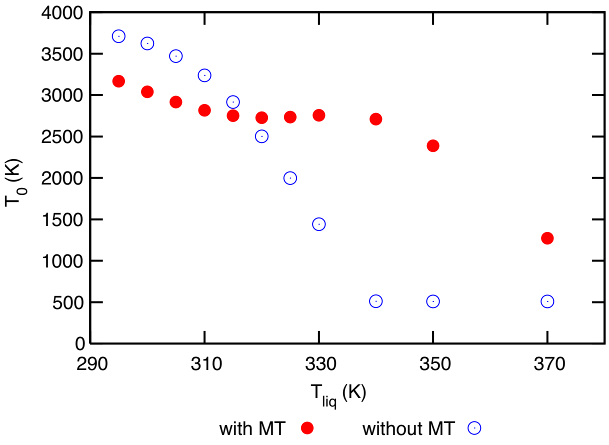


Fig. 9 Compression ratio vs. liquid temperature (*left*). Peak bubble pressure vs. liquid temperature (*right*)

Fig. 10 Peak temperature at bubble center vs. liquid temperature



298 to 350 K, this increment in the mass transfer flux enhances the bubble implosion because of two main reasons:

- An "extra" expansion is produced as a consequence of smaller density (Fig. 11).
- More water is fed into the bubble (Fig. 12). Due to the increment of the bubble water content, the condensation flux during the initial compression stage is larger. As a result, this stage is enlarged and the pressure attained during the collapse is extended.

When the liquid temperature is increased up to values around the boiling point (e.g. $T_{\text{liq}} = 370K$), the vapor pressure is so high that, being the minimum attainable pressure, the effective pressure wave amplitude is reduced diminishing also the degree of expansion.

Thus, as mass transfer becomes relevant, an important increase of the peak pressures is expected when the temperatures are far away from the boiling point ($T_{\text{liq}} < 340K$), whereas for high temperatures, the vapor pressure is so high that the effective amplitude of the liquid wave is significantly smaller, decreasing the violence of the collapse.

Fig. 11 Radius temporal evolution for different liquid temperatures

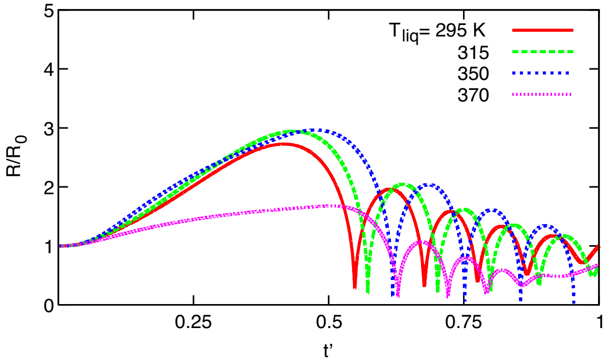
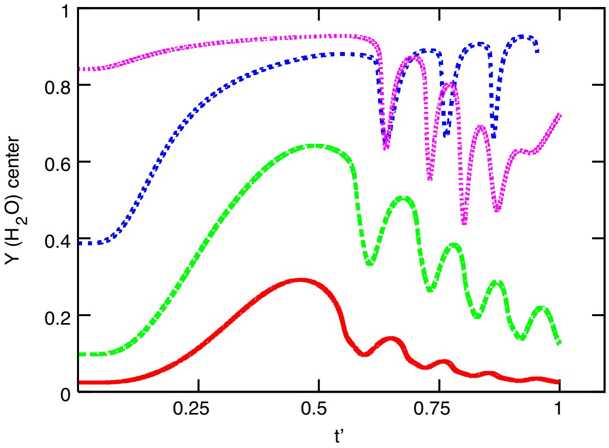


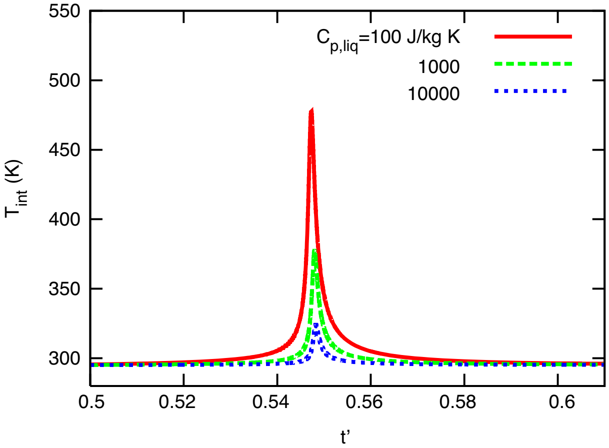
Fig. 12 Liquid temperature analysis. Water mass fraction temporal evolution inside the bubble. Color legend same as Fig. 11



In any event, it is important to draw the attention to the fact that the liquid temperature is the parameter dramatically modifying the trends when the mass transfer model is included. These trends provide some insight related with β whose correct values are still unknown [5]. Barber [1] produced one of the few available sensitivity analysis in SBSL showing that the light scattering, directly proportional to the implosion violence, when the liquid temperature is 1°C is about 200 times the emission at 40°C.

Figure 10 depicts the dependence of the peak temperature with the liquid temperature. The peak temperature substantially increases when the effect of mass transfer processes is not relevant. Thus, as it has been already suggested by Colussi & Hoffmann [4], this feature could constitute a proof of the small values of β for water in SBSL experiments.

Fig. 13 Liquid specific heat analysis. Interface temperature temporal evolution



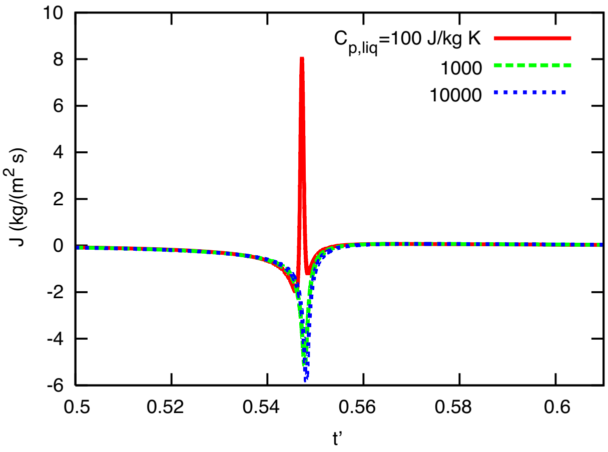


Fig. 14 Liquid specific heat analysis. Evaporation flux temporal evolution

8 Liquid Specific Heat Sensitivity Analysis

The liquid specific heat, $C_{p,\mathrm{liq}}$, has a very mild influence on the compression ratio, peak pressures and center temperatures, revealing that the influence of this parameter is minimal.

This variable mainly affects the temperature attained by the liquid around the bubble during the implosion, influencing the mass transfer phenomena across the interface. For liquids with extremely low specific heats, this becomes more important since less energy is required to increase the interface temperature, promoting evaporation processes. During the collapse, the interface temperature increases quickly (see Fig. 13). As a result, the effects of the temperature increment become more important than those of the pressure, making possible to predict evaporation processes during the implosion (Fig. 14). In principle, it could be helpful in order to feed mass inside the bubble during the period of higher pressure and temperature (when the chemical conversion rates might reach their highest values). However, evaporation processes tend to decrease the implosion violence because the bubble pressure increases faster.

It must be recalled that very low values of $C_{p,l}$ are required to predict evaporation during the collapse (for example, liquid mercury is one of the few substances with an specific heat around 100 J/kg K). In any case, evaporation processes are possible under exceptional conditions during the collapse.

9 Liquid Compressibility Sensitivity Analysis

The effect of liquid compressibility on the bubble dynamics is small. Increasing c_l, tends to slightly augment the peak temperatures the peak pressures and the amplitude of the rebounds. As the liquid compressibility increases (lowering c_l), a part of the energy involved in the implosion is used for compressing the liquid, lowering the bubble compression efficiency. However, during the expansion, the effect of the liquid compressibility on the bubble dynamics is negligible, when the low liquid pressure is not high enough to induce significant liquid density changes.

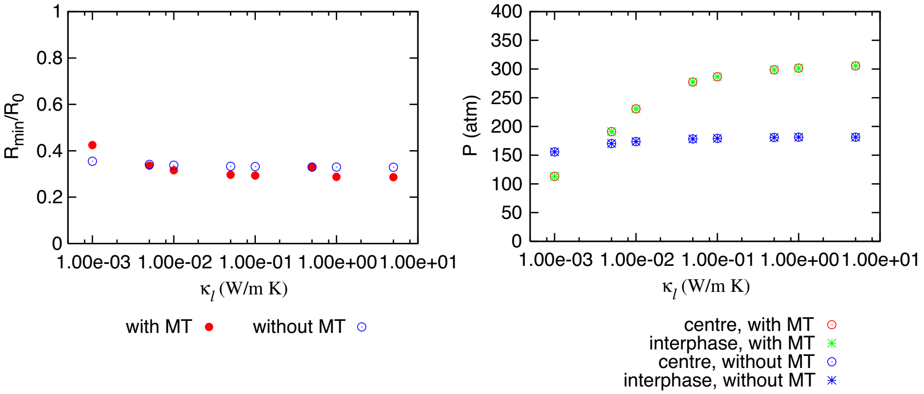


Fig. 15 Compression ratio vs. liquid conductivity (*left*). Peak bubble pressure vs. liquid conductivity (*right*)

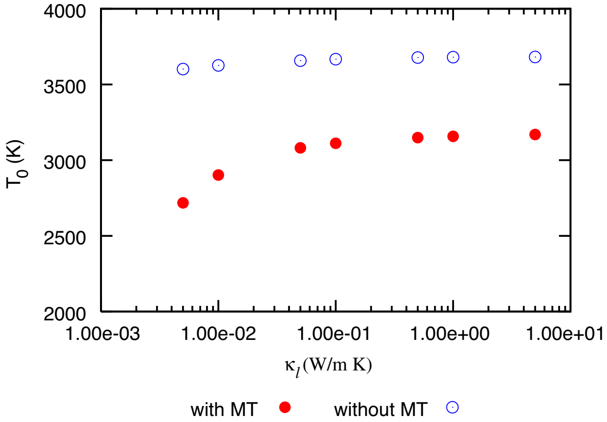
10 Liquid Conductivity Sensitivity Analysis

The liquid conductivity influences the liquid heat transfer between the bubble and the surrounding liquid. The effect of this parameter is more pronounced for small values because the heat transfer across the thermal boundary layer in the liquid controls the global process of heat exchange.

Mass transfer across the interface are linked with heat transfer processes and, therefore, with the liquid conductivity, specially for small values. Should MT be relevant the effects of liquid conductivity on bubble dynamics are essential (Figs. 15 and 16).

Independently of the importance of the mass transfer, for large conductivities an asymptotic limit appears for which the peak temperature, for example, reaches a constant value. In that case, the liquid heat transfer is not the limiting process and the role of conductivity is irrelevant.

Fig. 16 Peak temperature at bubble center vs. liquid conductivity



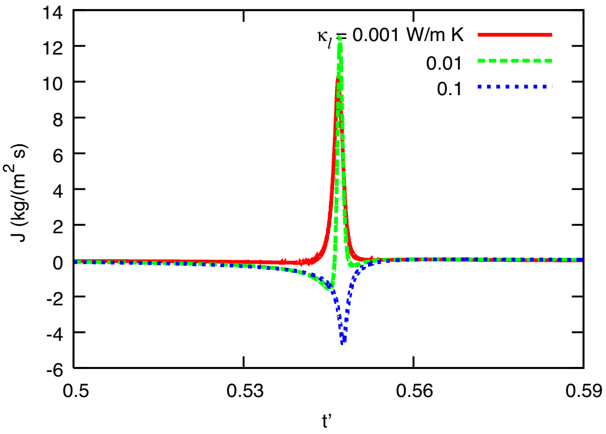


Fig. 17 Liquid conductivity analysis. Mass transfer flux across the interface during the implosion

If the liquid conductivity is large enough, the liquid heat transfer is not the limiting process and its conductivity has no influence on the process.

For those situations controlled by the liquid heat transfer, should the liquid conductivity be decreased, the heat transfer is impeded. As a consequence, the bubble temperature increases quickly for low conductivities with and without mass transfer. This fact bears an important impact upon the bubble implosion; the temperature increase tends to augment the bubble pressure faster, shortening the acceleration stage and reducing the implosion velocity. In other words, during the initial compression, an isothermal process results in a more violent implosion than an adiabatic one. This effect is stronger when mass transfer is included. Large liquid conductivities yield lower interface temperatures during the collapse and higher condensation fluxes; this enlarges the initial compression stage, resulting in higher compression velocities.

Regarding the influence of the liquid conductivity on the predicted evaporation/condensation flux, it must be noticed that the interface temperature is greatly influenced by the liquid conductivity. Thus, for low conductivity values, the interface temperature increases so quickly that even evaporation conditions are possible during the implosion. Note that the evaporation flux presents a maximum for low conductivity values (Fig. 17). For very low conductivities, a negative effect appears: as evaporation starts sooner, pressure increases faster stopping the implosion. Because of that, an optimum evaporation flux appears. As the liquid conductivity becomes larger, the collapse is more intense until the asymptotic value (in which heat transfer is not controlled by the liquid) is reached. As a consequence, large liquid conductivity values enhance the peak pressure and temperature, mainly for those cases in which mass transfer becomes important.

11 Liquid Viscosity Sensitivity Analysis

The viscosity effect is depicted in Figs. 18 and 19. Three different zones can be observed:

- For low viscosities, implosions are predicted with no influence of this variable.
- For high viscosities, no implosions occur.

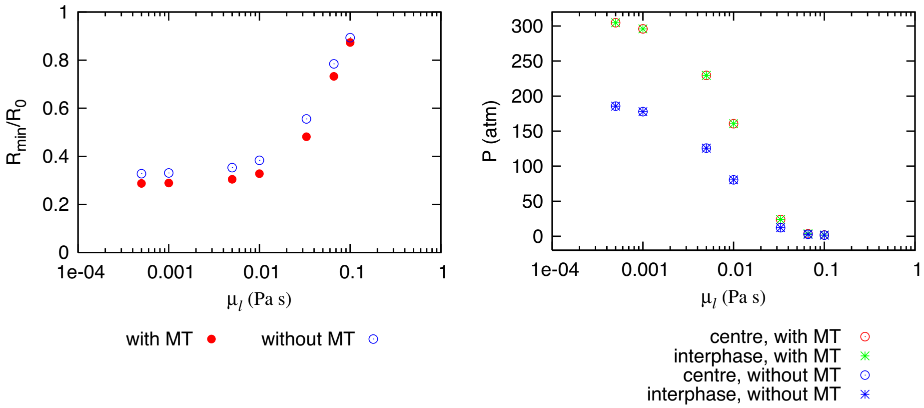


Fig. 18 Compression ratio vs. liquid viscosity (*left*). Peak bubble pressure vs. liquid viscosity (*right*)

- For intermediate viscosities, a transition zone appears in which the violence of the implosions decreases as the viscosity increases.

For viscosity values such that the viscous terms are negligible, the liquid motion is governed by the pressure and inertia forces. On the contrary, large viscosity values imply low Reynolds number flow with low velocities both in the liquid and at the bubble interface.

Thus, in order to enhance cavitation processes, the liquid viscosity must be under a threshold value which, for this particular example, can be taken as 0.01 Pa s.

12 Gas Specific Heat Sensitivity Analysis

The gas specific heat, $C_{p,\text{gas}}$, has a significant influence upon peak bubble variables.

Again, one must keep in mind that the evolution of the bubble temperature during the initial compression dramatically influences the final intensity of the collapse.

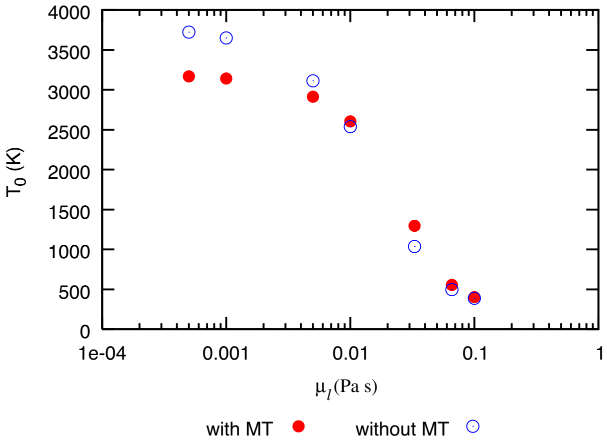


Fig. 19 Peak temperature at bubble center vs. liquid viscosity

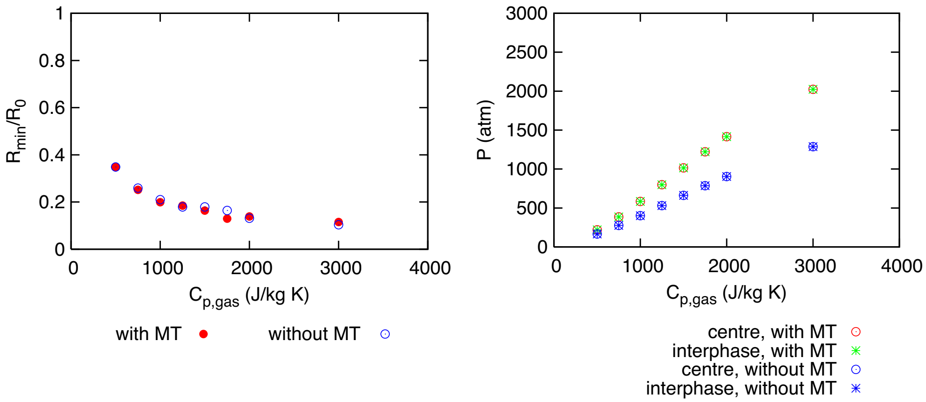


Fig. 20 Compression ratio vs. bubble specific heat (*left*). Peak bubble pressure vs. bubble specific heat

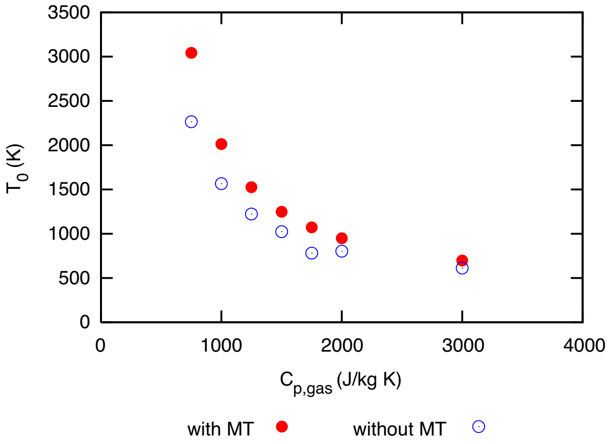
Large gas specific heats make more difficult to increase the bubble temperature, which tends to make the initial compression closer to isothermal As previously explained, this effect enhances the compression velocities and smaller compression ratios are reached (Figs. 20 and 21).

13 Gas Conductivity Sensitivity Analysis

The gas conductivity, κ_g, is a relevant value for the bubble dynamics, as depicted in Figs. 22 and 23. Like the liquid conductivity, this variable has an important impact on the heat exchange processes between the bubble and the surrounding liquid, which finally influences the intensity of the implosion.

Like the liquid conductivity, this property has an important impact on the heat exchange processes both, inside the bubble and between it and the surrounding

Fig. 21 Peak temperature at bubble center vs. bubble specific heat



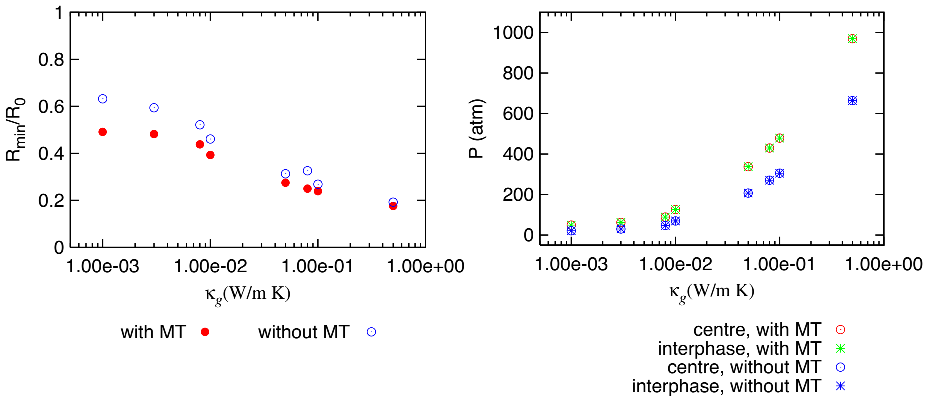


Fig. 22 Compression ratio vs. gas conductivity (*left*). Peak bubble pressure vs. gas conductivity (*right*)

liquid. This finally influences the intensity of the implosion. Regarding the peak pressures, an increment in the gas conductivity makes the initial compression closer to isothermal resulting in larger compression velocities and higher peak pressures.

On the other hand, although increasing the gas conductivity maximizes the intensity of the implosion, the heat exchange is also enhanced. This leads to the existence of an optimum value of κ for the peak temperature:

- On one side, large conductivities tend to cool down the bubble during the implosion, reducing its peak temperature.
- On the other hand, during the beginning of the compression stage, the cooling effect tends to prolong the acceleration stage, increasing the interface velocities.

The gas conductivity has also an effect on the expansion stage, which stresses the effect of this variable on the obtained results. During the expansion, the pressure

Fig. 23 Peak temperature at bubble center vs. gas conductivity

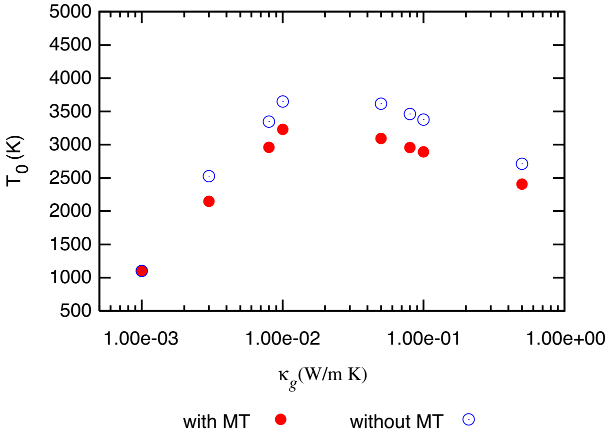
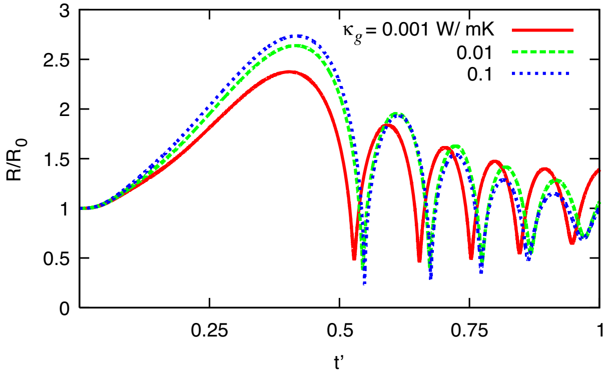


Fig. 24 Gas conductivity analysis. Radius temporal evolution



variations are imposed by the driving wave. Along this stage, the pressure and the bubble temperature decrease at the expense of the bubble density. Thus, those bubbles in which the temperature tends to remain constant (high conductivity) undergo large density reductions which are related with a higher expansion velocities (Fig. 24). As a result the compression is delayed due to the higher kinetic energy acquired by the liquid which, finally, strengthens the implosion.

To summarize, two different tendencies are observed and an optimum value appears:

- For small values, an increment of the conductivity enhances the expansion and delays the implosion, increasing the violence of the collapse. For this particular case this situation appears from $\kappa_g = 0.001$ to 0.01.
- For large conductivity values, the expansion enhancement is not important because the temperature remains constant independently from κ_g. During the implosions, the larger cooling effect during the compression is the cause of longer acceleration stages and higher peak pressures (as the bubble is compressed up to a smaller radius). However, in this zone the peak temperatures decrease because of the cooling effect produced by the conductivity increment.

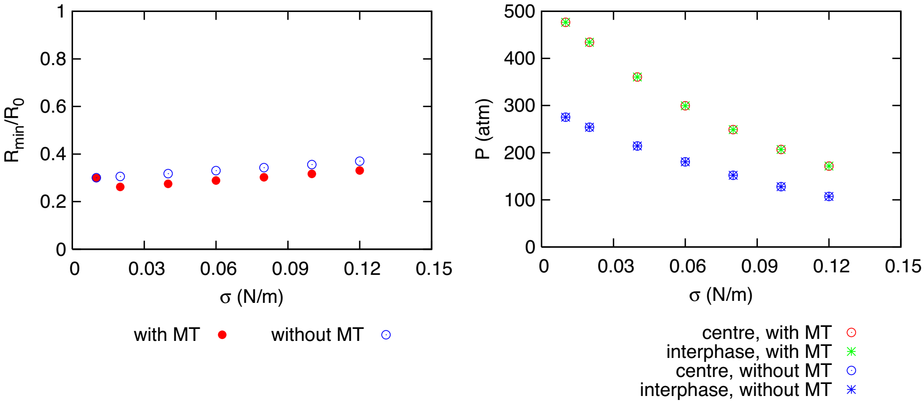


Fig. 25 Compression ratio vs. surface tension (*left*). Peak bubble pressure vs. Surface tension (*right*)

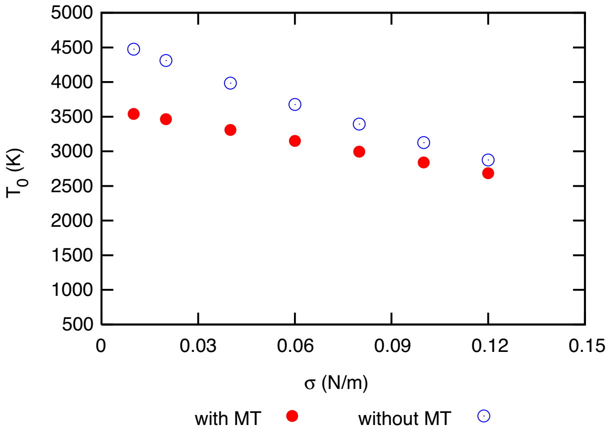


Fig. 26 Peak temperature at bubble center vs. surface tension

14 Surface Tension Sensitivity Analysis

A surface tension σ increment reduces the peak temperatures and pressures reached during the collapse (Figs. 25 and 26). Surface tension acts as an additional resistance which must be overcome to produce the bubble expansion. Thus, as surface tension becomes larger, the expansion velocity is smaller and the implosion is produced sooner and less violently.

15 Summary of the Most Relevant Results

From the previous parametric analysis, the following conclusions are obtained.

Among the liquid variables, the ratio between the driving pressure amplitude, ΔP, and the reference pressure P_{liq} is the most important parameter determining the violence of the bubble collapse. This ratio must be around 1, and, in any case, cannot be smaller than 0.9.

The liquid temperature has an important effect on the peak temperature and pressure during the implosions. Moreover, this parameter strongly influences the mass transfer model and the accommodation coefficient. Even though the peak temperatures increase when the liquid temperature decreases, the sensitivity is higher when the β coefficient is smaller, having a maximum sensitivity when no mass transfer is taken into account.

Experimental work shows that at 20 kHz the light emission is highly sensitive to bubble temperature [1], indicating that mass transfer processes are not dominant. This could be verified by selecting low values of β and high frequencies which do not allow to reach equilibrium conditions inside the bubble.

The mass transfer importance is influenced by the properties of the liquid and the gas as well as by the frequency. For given liquid and gas, the frequency is the main parameter determining the importance of the mass transfer process on the bubble behavior. At low frequencies mass transfer is always important and transient effects on mass transfer are negligible, being the equilibrium hypothesis applicable at the interface. At high frequencies, the bubble dynamics is mainly governed by gas inertia.

Mass transfer, which significantly influences the radius evolution at low frequencies, has no an appreciable effect on the bubble radius evolution.

For the example considered in this analysis, it is found that the viscosity influences the bubble behavior only when it is above 0.01 Pa s. It is impossible to produce violent implosions for values higher than 0.1 Pa s.

Liquid conductivity becomes important when the liquid heat transfer is the limiting process of the global heat flux:

- For values below 0.1 W/(m K), the liquid conductivity determines the total heat transferred across the interface. As its value is decreased, the implosion becomes less violent.
- For higher values, heat transfer is controlled by the gas and an increment in the liquid conductivity has no effect on the bubble.

Other liquid properties like mass density, specific heat and compressibility have a small effect on the bubble dynamics. The compressibility influences the resonance frequencies in the vessel as well as the characteristic distances in the liquid; therefore, this variable should be taken into account for the analysis of the global process.

The bubble gas specific heat has a great influence on the predicted peak temperatures and pressures. Extreme conditions are enhanced for low gas specific heats. This is evidenced by Argon that possesses one of the lowest specific heat values, while the measured sonoluminiscence is maximum [2, 10].

Gas conductivity has the strongest effect among all the gas parameters. For liquids, an increased gas conductivity always enhances the peak pressures. Two mains reasons can be argued:

- During the initial expansion, heat transfer is influenced by this parameter. For low values, the bubble is cooled during the expansion, which diminish the expansion degree and lowers the collapse intensity.
- During the initial compression, pressure increases because of the temperature and density rise. During this stage bubble shrinking is accelerated until the bubble pressure equals the bulk liquid pressure. The largest compression velocity would be obtained if all the pressure rise would be produced by the density increment. The bubble temperature is also increased, shortening this stage and reducing the implosion violence. Thus, the higher the conductivity, the smaller the temperature increment, the longer the initial compression stage and the stronger the collapse.

Regarding the peak temperature, two different phenomena are counteracting:

- On one side, strong implosions increase the peak temperatures (as just discussed).
- On the other hand, the high gas conductivities enhance the bubble heat transfer and decrease the bubble temperature.

As a result, an optimum value of gas conductivity appears for which is a maximum temperature.

Finally, the surface tension acts as an extra resistance which opposes the bubble movement during the expansion. Its importance is modest but it reduces the peak pressures and temperatures.

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