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THE EFFECT OF COMPRESSOR OIL ON THE SPEED OF SOUND IN MULTIPHASE / MULTICOMPONENT FLOW OF A REFRIGERANT

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This study examines the speed of sound in the refrigerant R134a intermittent two-phase flow in a horizontal annular duct of 8 mm inner diameter under the influence of a PAG oil (SP-A2) experimentally with the two-microphone method. Pressure pulsations, which originate from the compressor and propagate against flow direction through the evaporator to the test section were measured with four piezoelectric pressure sensors. Two-phase flow pattern was monitored by a high speed camera. The time delay of the pressure signal was determined by cross correlation function (ccf) in combination with bootstrap-resampling for estimation of uncertainty for the expected value of the ccf. Quality was varied between 0.05 and 0.2 kg vapor/kg total and contents of compressor oil between 0 and 10 % by mass. At mass fluxes of 400 kg/(m²s) or less the flow pattern was mainly slug flow with well separated phases. The pressure pulsations propagated as plane waves with a speed of sound close to that of the lighter phase in agreement with two-dimensional acoustic wave propagation theory for separated phases in horizontal ducts. At mass fluxes of 600 kg/(m²s) or above, the flow regime was still intermittent but the phases were well mixed. The pressure pulsations propagated slower than they would have done in single phase fluids in agreement with acoustic wave propagation theory for homogeneous mixed phases. The presence of compressor oil SP-A2 in the refrigerant flow had no measurable influence on acoustic wave propagation for the examined fluids at the stated operating points.
Keywords: SPEED OF SOUND, MULTIPHASE FLOW, TWO-MICROPHONE METHOD, R134A, COMPRESSOR OIL

1. Introduction

The speed of sound in multiphase systems is of interest for a wide range of applications: Acoustic properties and appearance of choked flow in multiphase flows, safety in atomic reactors, damping of explosions with aqueous foams, medical applications and measurement of distance in aquatic systems for civil and military use. The available experimental studies focussed primarily on the measurement of the speed of sound in bubbly flows of water/air ([1], [2], [3], [4], [5], [6], [7], [8]) and water/steam mixtures ([9], [10], [11], [12], [4]). Experimental data on separated ([4]) and intermittent ([4], [6], [7]) flow compositions is rare and limited to water/air or water/steam mixtures. An exception is the publication of Jourdan on the speed of sound in aqueous foams [13]. There are various theories for wave propagation velocity in the different multiphase flow patterns. Some of them have proven to be valid for homogenous mixed phases (e.g. [14] in [4] and [8]) and separated flow compositions of water/air and water/steam systems (e.g. [4]). If these models are also valid for other fluids and multicomponent systems is there to be proven.

The aim of this study is to prove the validity of the wave propagation velocity models for homogenous mixed phases and separated composition for the refrigerant R134a, also under the influence of a PAG oil (SP-A2).

2. Theoretical considerations

The (isentropic) speed of sound c is a thermodynamic state variable and independent of the frequency and amplitude of the pressure waves. For wave propagation in tubes or channels the speed of sound is dependent on wall geometry and elasticity according to [15]. If more than one component and/or phase are present and the fluid(s) flows through a tube or channel a physical model of the acoustic behaviour of the system is needed. Since only well mixed or well separated fluid flows are examined in this study, only the corresponding speed of sound models will be presented in the following.

2.1 Speed of sound in homogenous mixed phases

There are various models for predicting the speed of sound in homogenous mixed phases in one component. The model of Wood [14] is well known and shows good agreement with measurement data in mixtures of water/air and water/steam according to Henry [4], as can be seen in Fig. 1. It will be used as a reference model for all measurements in well mixed phases:

$$c_m^{-2} = \left(\frac{\alpha}{c_g^2 \cdot \rho_g} + \frac{(1-\alpha)}{c_l^2 \cdot \rho_l} \right) \cdot \left(\alpha \cdot \rho_g + (1-\alpha) \cdot \rho_l \right) \tag{1}$$

where α is the void fraction of the gas and vapor phase respectively, ρ is the density and the indices g , l and m describe the gas/vapor phase, the liquid phase and the mixed phase. The speed of sound in homogenous mixtures of vapor and liquid phase is far below that of the individual phases, since the compressibility of the mixture is mainly dependent on void fraction of the vapor phase, but the density is mainly dependent on liquid fraction.

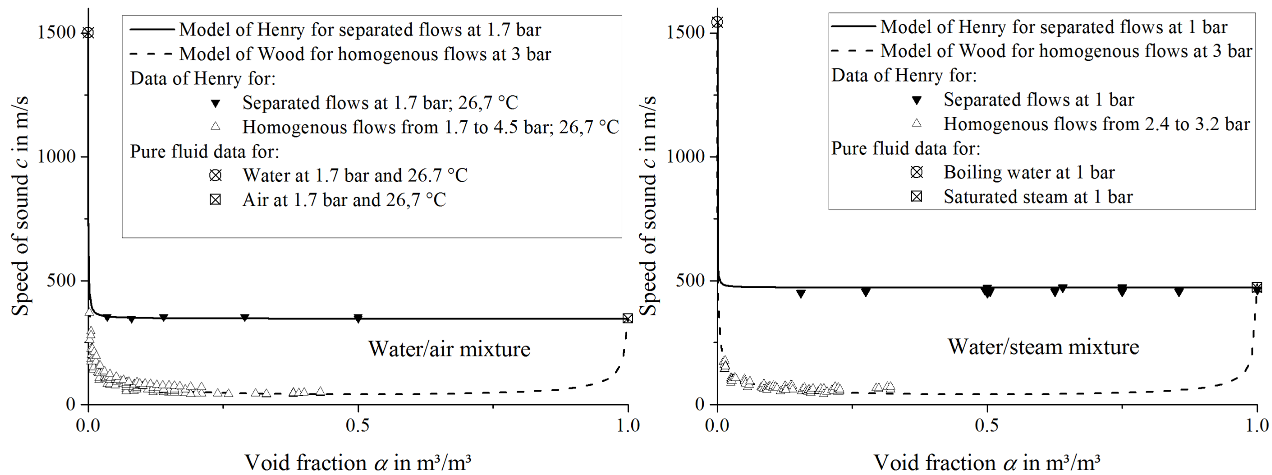

Figure 1: Left: Speed of sound in bubbly and separated flow of water/air mixtures from [4]; Right: Speed of sound in bubbly and separated flow of water/steam mixtures from [4]; both compared to the Models of Henry and Wood

One of the assumption of Wood's model is that the phases are homogenous mixed and move with the same velocity, the slip ratio is one. If this assumption is valid, the flow velocity of the mixture can be calculated by following equation:

$$w = \frac{\dot{m}}{\rho_m \cdot \pi \cdot r_i^2} \tag{2}$$

where w is the velocity of the mixture, $\dot{m}$ is the steady state mass flow in the system, $\rho_m = \alpha \cdot \rho_g + (1-\alpha) \cdot \rho_l$ is the mean density of the mixture and r_i is the inner radius of the tube. If the void fraction α is unknown it can be calculated with given quality x for a slip ratio of one:

$$\alpha = \left(1 + \left(\frac{1-x}{x}\right)\frac{\rho_g}{\rho_l}\right)^{-1} \tag{3}$$

2.2 Speed of sound in separated compositions

There are different models for the speed of sound in separated compositions. The Model of Henry [4] shows overall good agreement with experimental data of Henry [4] in Fig. 1. In this study the model of Henry will be used as a reference model for all measurements in separated flow conditions:

$$c_m^2 = c_g^2 \left(1 + \frac{1-\alpha}{\alpha} \cdot \frac{\rho_g}{\rho_l}\right) \tag{4}$$

For void fractions of 0.2 and above the model speed of sound is close to that of the lighter phase of the fluid.

3. Test setup

The main components of the experimental setup are shown on the left side of Fig. 2. On the right side of Fig. 2 an exemplary refrigeration cycle is shown in a log p,h-diagram of the used refrigerant R134a. The Hanon electric scroll compressor is the main source of pressure fluctuations in the refrigeration cycle. These fluctuations propagate through the pipes and the components in and against flow direction. In the test section the refrigerant/oil-mixture (R134a/SP-A2) is in two-phase state. The amount of oil in the test section was set by the needle valves after the oil separator, the volumetric oil flow was measured by a Kobold DZR-1 gear flowmeter. The mass flow was controlled by the second electric expansion valve and was measured by an Emerson CMF025M coriolis mass flow meter. The test section pressure was controlled by the speed of the compressor and was measured by WIKA S-20 pressure transmitters. The subcooling of the refrigerant was controlled by the two subcoolers. All thermodynamic data of R134a was calculated with the help of the REFPROP database. Temperatures were measured by thermocouples type K. For data acquisition a cDAQ-9178 chassis with a NI 9214 and a NI 9208-module from National Instruments in combination with LABVIEW 2016 were used.

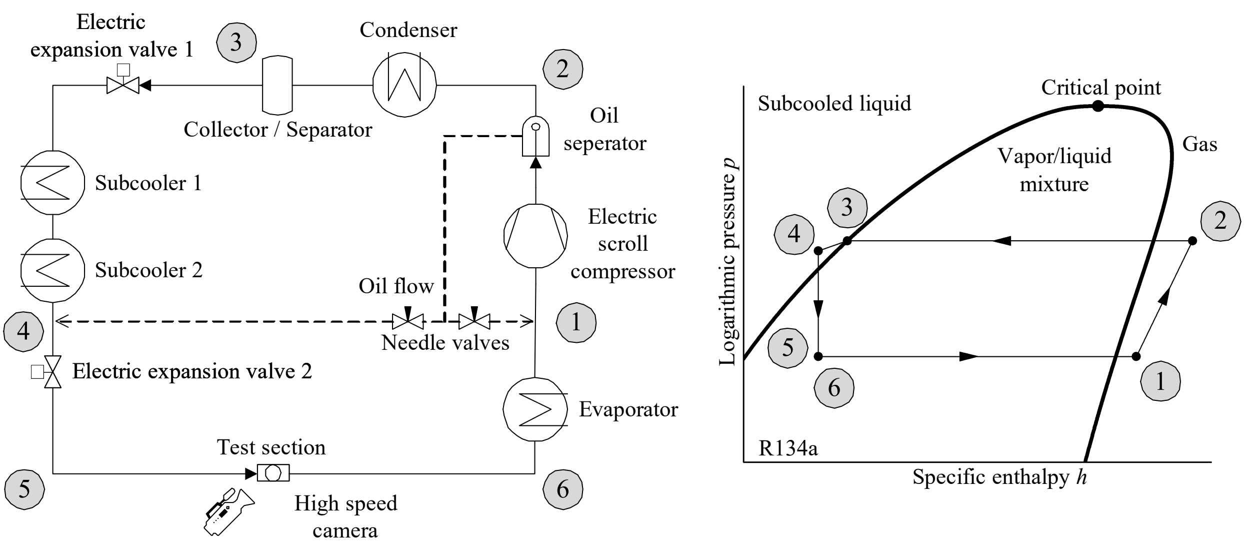

Figure 2: Left: A schematic of the main components of the experimental setup; Right: Exemplary refrigeration cycle (state points 1-6) in the log p,h-diagram of R134a, the test section was in between point five and six

The high speed camera was a MegaVis HD from High Speed Vision GmbH. The used frame rate at all experiments was 3200 fps at a resolution of 1920x168 pixels. It was possible to record about seven seconds with these settings. The camera was triggered by a TTL-signal of the NI 9264 digital module.

3.1 Test section

The test section was designed to measure the time delay of acoustic pressure signals in the refrigerant/oil flow with the two-microphone method. A CAD rendering of the test section is shown in Fig. 3. The distance between the test section and the next bend upstream was about ten times of the inner diameter, so that the flow is assumed to be hydrodynamic stable according to [16]. A glass tube was fixed in position between two brass fittings with the help of two steel plates and four threaded rods. A pair of piezoelectric pressure sensors (PCB 112A22) were installed flush to the circular inner wall in each brass fitting, one vertically from above, the other one vertically from below. The arrangement of the piezoelectric pressure sensors allows to measure the time delay in each phase if they are well separated. For data acquisition a NI 9234 module from National Instruments was used.

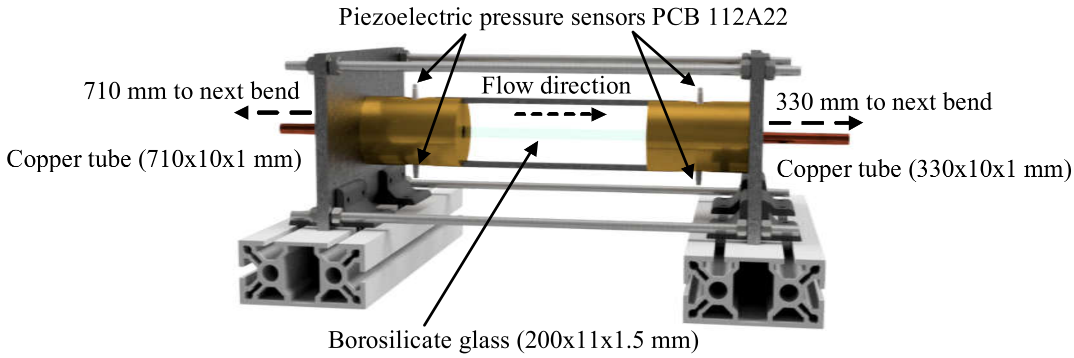

Figure 3: CAD rendering of the test section

3.2 Test procedure and evaluation routine

Each measurement was carried out at a defined stationary operation point of the test stand. All sensor signals except for the piezoelectric pressure sensors were recorded at 1 Hz during the entire measuring process. At the beginning of each measurement, the high speed camera was triggered and the signals of the piezoelectric pressure sensors were recorded at 51200 Hz. For post processing MATLAB R2016b and the Signal Processing Toolbox 7.3 were used. The cross correlation function (ccf) was used to estimate the time delay of two acoustic pressure signals:

$$r_{s_2,s_1}(\Delta t) = \sum_{t=-\infty}^{\infty} s_2(t) \cdot s_1(t+\Delta t). \tag{5}$$

where r is the correlation value, s_1 and s_2 are the discrete signal time series and Δt is the time shift. The time delay of two signals is the time shift associated with the maximum correlation value. The ccf is robust against noise in signals, but dependent on signal length as shown in [17]. A possibility to increase the validity of the ccf is to do it over and over again with random signal lengths: This statistical resampling-method is called bootstrapping [18]. In Fig. 4 a histogram of a bootstrap (n=1000 samples) of the time delay estimated with the ccf of two simulated sinusoidal signals is shown. The signals are both 1s long, have a frequency of 10 Hz, are sampled with 51200 Hz and have a phase shift of 0.01 s against each other. The time shift and the expected value respectively are the time delay associated with the maximum of the histogram.

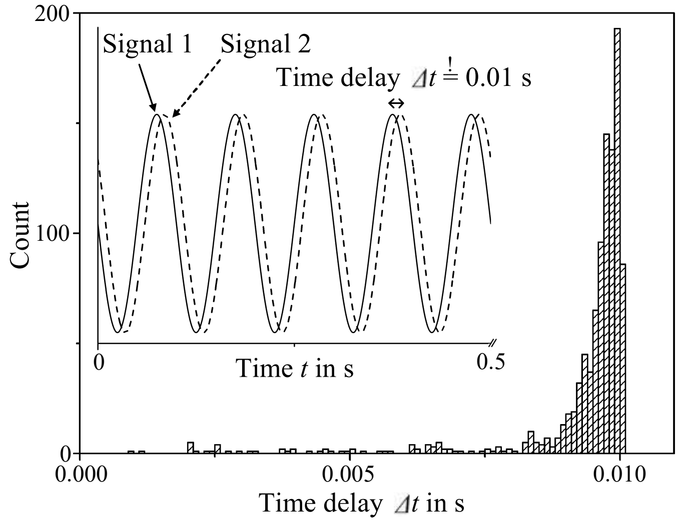

Figure 4: Histogram of a bootstrap (n=1000 samples of different length) of the time delay estimated with the cross correlation function of two simulated sinusoidal signals with a phase shift of 0.01s

For this study the time series length was six seconds, the resampling was done 1000 times for each measurement and the final time delay was estimated by taking the mean value of all time delays in the maximum bin of the histogram. Uncertainties in this study were calculated according to the guide to the expression of uncertainty in measurement from 2008 [19]. The type A evaluation of standard uncertainty of the final time delay was carried out differently: The experimental standard uncertainty was calculated with the final time delay and the 1000 sample-time delays of the bootstrapping. The measured propagation velocity was corrected by the flow velocity of the fluid using Eq. (2) and Eq. (3), even in separated flow conditions. Measurement results with combined standard uncertainties higher than 10 % or wave propagation velocities near zero were not considered. The influence of the tube wall material on the wave propagation velocity is smaller than 0.2 % according to theory of Löwy [15] for the experimental setup in this study and will be neglected.

4. Experimental results

The speed of sound was examined experimentally at varying mass flux and vapor quality. Exemplary frames of the recordings of the high speed camera (Fig. 5) show intermittent flow behaviour for all examined points in this study. Also a trend to stratification of flow is clearly visible, even at high mass flux. The mixing of phases increases with mass flux. The influence of the content of compressor oil will be discussed later. The flow pattern map of Wojtan, Ursenbacher, Thome from 2005 for flow boiling in horizontal tubes [20] indicates that all examined points in this study are in intermittent and slug flow regime (Fig. 6).

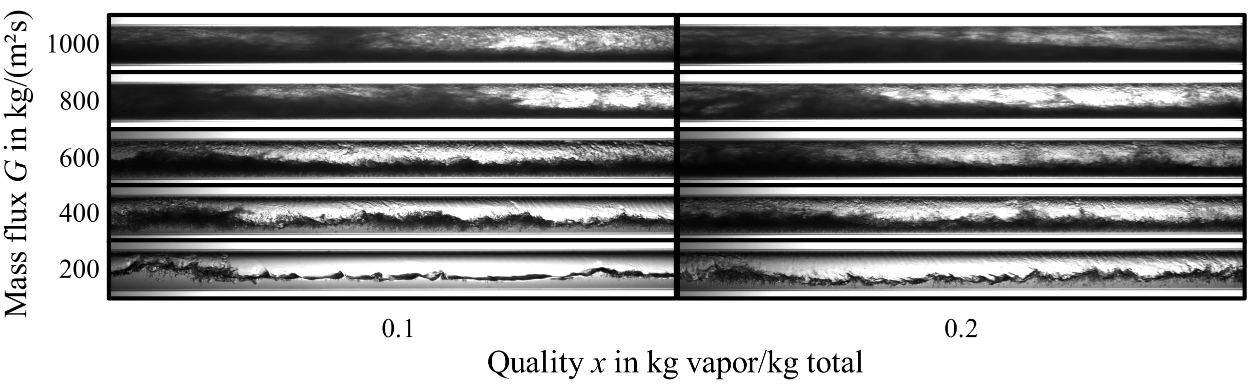

Figure 5: Exemplary frames of the recordings of the high speed camera at varying mass flux and quality

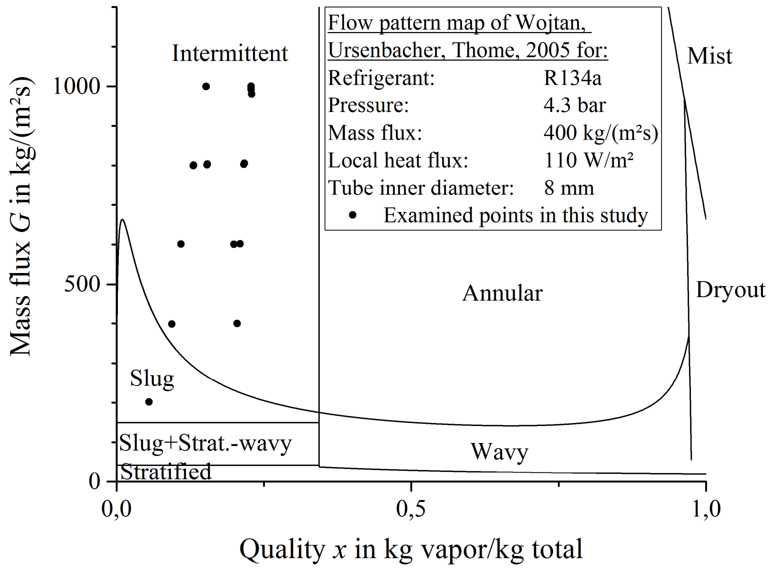

Figure 6: The Wojtan, Ursenbacher, Thome flow pattern map for flow boiling in horizontal tubes for R134a [20]; the examined points in this study are all in intermittent and slug flow regime

4.1 Speed of sound at varying mass flux

The speed of sound was measured at mass flux varying from 200 to 1000 kg/(m²s) and two main vapor qualities (0.1 and 0.2 kg/kg). The pressure in the test section varied between 4.0 and 4.6 bar. The compressor speed varied between 800 and 6000 rpm. There was to be supposed no compressor oil in the test section. The results of the ccf indicated that the pressure pulsations propagate against flow direction through the test section. The speed of sound in Fig. 7 for low mass flux (200 and 400 kg/(m²s)) is close to the speed of sound in single vapor phase of about 146 m/s for both sensor pairs. The model of Henry (Eq. (4)) can be used to explain these measurement results as pressure pulsations which propagate as plane waves in stratified flow compositions. For higher mass flux (600 to 1000 kg/(m²s)) the speed of sound is lower than in single phase composition (pure vapor: 146 m/s; pure liquid: 560 m/s) in agreement with theory of Wood for homogenous mixed phases (Eq. (1)). Both stated speed of sound models describe the upper and lower limit for wave propagation velocities in multiphase flows of vapor and liquid.

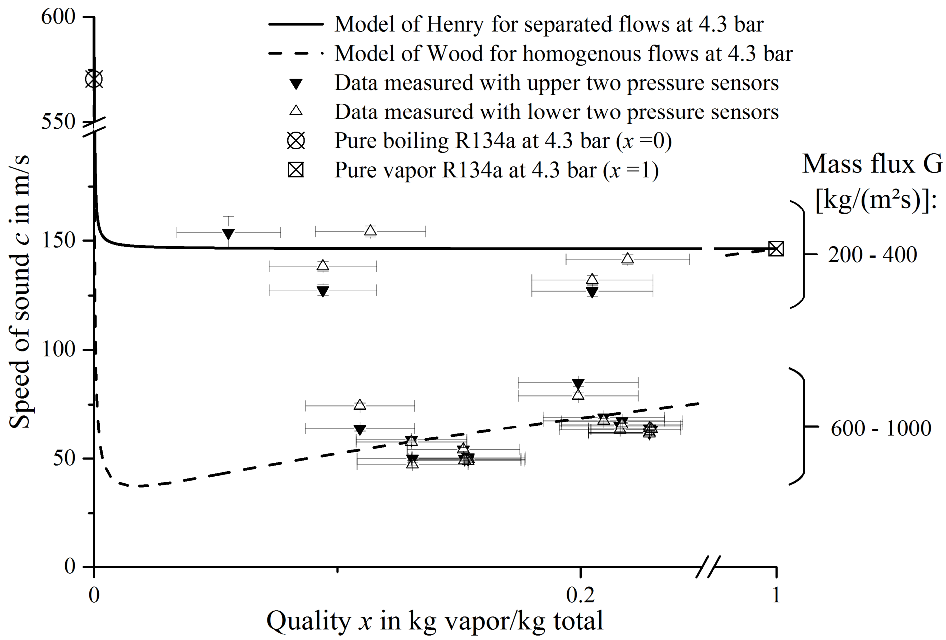

Figure 7: Speed of sound in two-phase flow of R134a at mass flux from 200 to 1000 kg/(m²s), varying pressures from 4.0 to 4.6 bar and varying compressor speed from 800 to 6000 rpm

4.2 Speed of sound at varying compressor oil content

The speed of sound in this part of the study was measured at two mass fluxes (200 and 600 kg/(m²s)) and two main vapor qualities (0.1 and 0.2 kg/kg). The content of the PAG oil (SP-A2) was varied between 0 and 10 % by mass. The pressure in the test section varied between 4.3 and 4.6 bar. There are two levels of speed of sound in Fig. 8, one close to the speed of sound of the pure vapor phase which can be explained by the Model of Henry (Eq. (4)) and the other one considerably lower which can be explained by the Model of Wood (Eq. (1)).

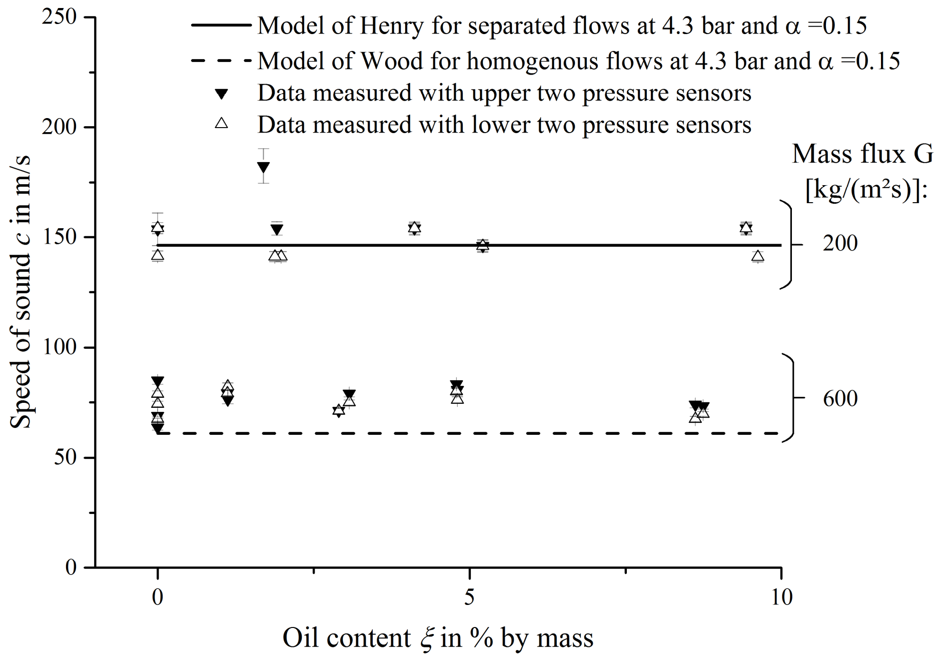

Figure 8: Speed of sound in two-phase flow of R134a/SP-A2 mixtures at two mass fluxes (200 and 600 kg/(m²s)), varying pressures from 4.3 to 4.6 bar and varying compressor speed from 800 to 2050 rpm

The measurement results of Fig. 8 indicate that there is no influence of the compressor oil on wave propagation velocity. The videos of the high speed camera indicated that there was no difference in flow pattern at different compressor oil contents at the stated operating points. Since the compressor oil certainly has a much higher density and speed of sound than the vapor phase of the refrigerant, the measurement results match the physical model of wave propagation in multiphase flow. There is no speed of sound data available to the authors for the compressor oil SP-A2; corresponding measurements should be carried out in the future. The stated oil contents in the test section have a high uncertainty (> 10%). Oil concentration measurements are to be carried out in the future in order to prove the functioning of the oil supply system and to reduce the uncertainty. At higher vapor qualities the influence of the compressor oil on the flow pattern and the speed of sound of the multiphase / multicomponent system will significant, so corresponding measurements should be carried out in the future.

5. Conclusions

In this study the speed of sound in multiphase flow of the refrigerant R134a under the influence of a PAG oil (SP-A2) was examined experimentally with the two microphone method. At separated flow compositions the speed of sound is close to that of the lighter phase of the fluid according to wave propagation theory for separated flow compositions. This wave propagation velocity is the upper limit for the speed of sound in multiphase flows. The lower limit is represented by the speed of sound for homogenous mixed phases, which was demonstrated with experimental data in this study. The content of compressor oil had no effect on wave propagation velocity in this study according to wave propagation models for multiphase flow.

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REFERENCES

1. Karplus, H.B., Rep. C00-248, The velocity of sound in a liquid containing gas bubbles, (1958).
2. Walle, F.v.d., Verheugen, A.J., Haagh, V.J.M. and Bogaardt, M., Rep. EUR 2336.2, A study of the application of acoustical methods for determing void fractions in boiling water systems, (1966).
3. Gibson, F.W., Measurement of the Effect of Air Bubbles on the Speed of Sound in Water, *The Journal of the Acoustical Society of America,* **5B**, 1195, (1970).
4. Henry, R.E., Grolmes, M.A. and Fauske, H.K., Rep. ANL-7792, Pressure-Pulse Propagation in Two-Phase One- and Two-Component Mixtures, (1971).
5. Böckh, P. von, *Ausbreitungsgeschwindigkeit einer Druckstörung und kritischer Durchfluss in Flüssigkeits/Gas-Gemischen*, Doctoral Thesis, University of Karlsruhe, (1975).
6. Padmanabhan, M., *Wave propagation through flowing gas-liquid mixtures in long pipelines*, Doctoral Thesis, Georgia Institute of Technology, (1976).
7. Sultan, K.M., *The propagation of pressure waves in two-phase gas/liquid flows*, Master Thesis, University of Western Ontario, (1999).
8. Wilson, P.S. and Roy, R.A., An audible demonstration of the speed of sound in bubbly liquids, *American Journal of Physics,* **10**, 975, (2008).
9. Karplus, H.B., Rep. ARF-4132-12, Propagation of pressure waves in a mixture of water and steam, (1961).
10. Collingham, R.E. and Firey, J.C., Velocity of Sound Measurements in Wet Steam, *Industrial & Engineering Chemistry Process Design and Development,* **3**, 197, (1963).
11. England, W.G., Firey, J.C. and Trapp, O.E., Additional Velocity of Sound Measurements in Wet Steam, *Industrial & Engineering Chemistry Process Design and Development,* **2**, 198, (1966).
12. DeJong, V.J. and Firey, J.C., Effect of Slip and Phase Change on Sound Velocity in Steam-Water Mixtures and Relation to Critical Flow, *Industrial & Engineering Chemistry Process Design and Development,* **3**, 454, (1968).
13. Jourdan, G., Mariani, C., Houas, L., Chinnayya, A., Hadjadj, A., Del Prete, E., Haas, J.-F., Rambert, N., Counilh, D. and Faure, S., Analysis of shock-wave propagation in aqueous foams using shock tube experiments, *Physics of Fluids,* **5**, 1-20, (2015).
14. Wood, A.B., *A textbook of sound*, The Macmillan Company, New York (1930).
15. Löwy, R., *Druckschwankungen in Druckrohrleitungen*, Springer, Wien (1928).
16. Baehr, H.D. and Stephan, K., *Wärme- und Stoffübertragung*, Springer-Verlag, Berlin, Heidelberg (2006).
17. Vio, R. and Wamsteker, W., Limits of the Cross-Correlation Function in the Analysis of Short Time Series, *Publications of the Astronomical Society of the Pacific,* **779**, 86, (2001).
18. Efron, B., Bootstrap Methods, *The Annals of Statistics,* **1**, 1, (1979).
19. Joint Committee for Guides in Metrology, Evaluation of measurement data - Guide to the expression of uncertainty in measurement, (2008).
20. Wojtan, L., Ursenbacher, T. and Thome, J.R., Investigation of flow boiling in horizontal tubes, *International Journal of Heat and Mass Transfer,* **14**, 2955, (2005).