MAY 14 1965

LA-DC-6945 (Full Paper)

84368

CONF-650611-1

LASL-AEC-OFFICIAL

The Generation of Oscillations Having Acoustic
Properties in Forced Convective Heat Transfer to Cryogen*

MASTER

by

Rodney S. Thurston

Los Alamos Scientific Laboratory, University of California

Los Alamos, New Mexico, U.S.A.

ABSTRACT

Heat transfer has been known to be capable of inducing acoustic phenomena for more than 100 years. In relatively recent heat transfer experiments, which developed large radial gradients of physical properties, oscillations at acoustic frequencies have been observed. These cases have included gaseous flow at very high heat fluxes, and heat transfer to fluids undergoing a change of phase or in the supercritical region. Investigations have been made of pressure oscillations appearing in forced convective heat transfer to initially liquid nitrogen and hydrogen in long small diameter flow channels. Some of the observed oscillations had characteristics similar to open-open pipe resonance and Helmholtz resonance. An analogy is presented between this phenomenon and that occurring in the Rijke tube, which was discovered in the last century.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

PATENT CLEARANCE OBTAINED. RELEASE TO
THE PUBLIC IS APPROVED. PROCEDURES
ARE ON FILE IN THE RECEIVING SECTION.

LASL-AEC-OFFICIAL

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Introduction

An observation that heat transfer can drive oscillations in gas flowing through a tube was made over a hundred years ago by Rijke¹. He observed that if a wire gauze is placed across the cross section in the lower half of a vertical tube and heated, then after withdrawal of the flame, the tube emanates sound and continues to do so until the mesh cools.

In 1960 McCarthy and Wolf² published results of forced convection heat transfer studies on gaseous hydrogen and helium in a heated tube. They reported that under some conditions the observed heat transfer was accompanied by pressure oscillations. Observed frequencies, which were on the order of 500 cps, corresponded to the fundamental acoustic frequency of the test section between two mixing chambers. Observed amplitudes varied from 5 to 20 psi, peak-to-peak.

Hines and Wolf³ reported severe pressure fluctuations accompanying forced convection heat transfer to supercritical RP-1, a rocket fuel. The frequencies ranged from 1000 to 10,000 cps at peak-to-peak amplitudes of 60 to 380 psi on a level of 700 psia, resulting in destruction of thin walled test sections. At pressures three times the critical pressure, this phenomenon was no longer observed. The frequencies generally corresponded to open-open pipe resonance, and at times the second harmonic was dominant.

Experiments performed at the Los Alamos Scientific Laboratory⁴, forcing two-phase hydrogen through an aluminum block, produced pressure oscillations which were simulated in frequency by the Helmholtz resonator concept. Peak-to-peak amplitudes were on the order of 1 to 4 psi, and frequencies varied from 30 to 8 cps.

Goldmann^{5,6} has observed the production of acoustic noise, which he describes as "heat transfer with a whistle", in forced convection heat transfer to two-phase and supercritical water. He has attributed this phenomenon to large property variations under nonequilibrium conditions.

A NASA publication⁷ contains a brief summary of investigations into two-phase flow oscillations, and presents a photographic study of such oscillations in hydrogen.

In this presentation, pipe resonance will be defined as the resonance associated with the fundamental wave length for an open-open pipe. For a pipe of length L , filled with

Superior numbers refer to similarly-numbered references at the end of this paper.

a fluid at uniform temperature, this resonant frequency is given by

$$\omega_p = c/2L \quad (1)$$

Helmholtz resonance is that resonance associated with a resonator composed of a cavity connected to an external atmosphere via an orifice or neck. The gas in the cavity is compressed and expanded by the motion of the fluid in the neck, analogous to a spring-mass system. The frequency of a Helmholtz resonator consisting of a neck, containing a mass m of fluid, attached to a cavity, with volume V_G , is given by

$$\omega_H = \frac{A}{2\pi} \left(\frac{\gamma P}{m V_G} \right)^{\frac{1}{2}} \quad (2)$$

Pressure Oscillations in Cryogenic Experiments

A series of experiments was performed at the Los Alamos Scientific Laboratory^{8,9} with the objective of testing the hypothesis that pressure oscillations accompanying forced convective heat transfer to cryogenics had acoustic properties. The horizontal test section (Fig. 1) was an insulated 2-3/4 inch diameter duraluminum rod with four holes of 3/16 inch diameter drilled through on a 1-1/2 inch circle. In some runs, three of the four holes were plugged for single channel flow studies. Static pressures were measured in both plena and one flow channel by transducers attached directly to the test section. Fluid temperatures were measured in both plena by platinum resistance sensors. The outlet plenum could have either of two volumes, depending on whether a volume filling plug was used. At the downstream end of the outlet plenum an orifice plate usually restricted the discharge flow to sonic velocities. Each experiment was initiated with the rupture of a frangible diaphragm at the upstream end of the test section. The experiment was terminated after the temperature of the test section remained close to the liquid temperature of the cryogen used.

Figure 2 presents a tracing of a record of a pressure oscillation in nitrogen. The fundamental frequency of this oscillation corresponds to that at which open-open pipe resonance can be expected. Its important characteristics are the second harmonic and the appearance of a large amplitude in the flow channel with diminished ones in the plena.

Figure 3 presents tracings of pressure oscillations in nitrogen at flow rates about an order of magnitude lower than those for Fig. 2. The two sets of tracings in Fig. 3 are from experiments with similar conditions, but different outlet plenum volumes. The frequency observed with an 8.15 cubic inch outlet plenum was 5.0 cps, while that

observed with a 26.9 cubic inch outlet plenum was 2.8 cps. The observed ratio of frequencies is 1.78, which differs by less than 4% from the ratio of 1.85 predicted by equation 2 for the Helmholtz mode. In contrast to the oscillations shown in Fig. 2, those of Fig. 3 exhibited equivalent amplitudes at all pressure transducers, including those in the plena.

The two types of pressure oscillations illustrated above can also appear superimposed on one another, as is shown in Fig. 4. The portion of a record illustrated there was obtained in a hydrogen experiment. These oscillations were observed for flow through one channel and for flow through four channels in parallel.

Figure 5 presents one condition which had to be satisfied before oscillations would appear in the apparatus of Fig. 1. That condition was that the temperature of hydrogen in the inlet plenum had to be equal to or less than the saturated vapor temperature at subcritical pressures, or the temperature at which specific heat is a maximum at supercritical pressures. Outlet plenum conditions for the data shown on Fig. 5 were in all cases to the right of the curve shown there. These observations were made under conditions of a transient cooldown which typically lasted 100 seconds. Experiments are currently being performed on an electrically heated test section, 1/4 inch I.D. by 10 feet long. Preliminary analyses of early tests with steady conditions confirm the nature of the phenomena observed in the cooldown.

Acoustic Properties of Pressure Oscillations

Two observed modes of pressure oscillation have been illustrated. One can compare their characteristics with those associated with open-open pipe and Helmholtz resonances.

The high frequency oscillations of the type shown in Figs. 2 and 4 exhibited much smaller amplitudes in the plena than at a flow channel location 16 inches from the outlet plenum. In the nitrogen experiments a second harmonic was also observed for this mode. These are characteristics of pipe resonance, in which the resonating system is confined to the flow channel, excluding the plena. Therefore it is not unreasonable to assume that this mode of pressure oscillation is that phenomenon.

The lower frequency oscillations shown in Figs. 3 and 4 displayed equivalent amplitudes in the flow channel and plena. This is characteristic of Helmholtz resonance since the plena are components of the resonating system. Two tests were applied with equation 2 to this mode of pressure oscillation. One, which was mentioned above, was the verification of the dependence of the frequency of this mode on the outlet plenum volume. The second test was based on the flow area dependence in equation 2. As is shown in Reference 9, reduction of the flow area from four channels to one channel,

reduced the resonant frequency by a factor of two. It is therefore reasonably certain that the flow of initially liquid nitrogen and hydrogen through the apparatus shown in Fig. 1 had a feature which was analogous to a spring-mass system.

Analogy with the Rijke Tube

The Rijke tube is a classical example of an acoustic pressure oscillation induced by heat transfer. The sound emanating from a Rijke tube occurs at a very dominant frequency associated with the resonant mode of the system. It has been shown that two of the types of pressure oscillations observed in the apparatus of Fig. 1 also displayed characteristics associated with the geometry and acoustical resonance.

A theoretical analysis of how heat transfer can drive acoustic oscillations in the Rijke tube was performed by Merk¹⁰. His model consisted of a disc-shaped heat source perpendicular to the axis of the tube, and placed within the tube. He applied perturbation analysis to the steady state equations for the conservation of mass, momentum, and energy. He then derived a complex characteristic equation by matching boundary conditions on both sides of the disc. The real part of the characteristic equation gives an instability criterion, and the imaginary part gives the frequency at which the instability begins.

Merk's equations show how energy is converted from a thermal mode into an acoustical mode for the case of a simple geometry and an ideal gas with constant properties. Although the geometry and fluid properties of the experiments discussed herein are not at all as simple as in the Rijke tube, the significance of Merk's analysis is that it is a well understood example of heat transfer driving resonant acoustical oscillations.

In the Rijke tube, heat transfer from the wire gauze to the gas in natural convection is seen to be very sensitive to flow disturbances. The analogous sensitivity of heat transfer to disturbances in the forced convection of cryogens through warm tubes could possibly be caused by the flux of thermal energy across layers having large gradients of physical properties. The thickening and thinning of these layers by flow disturbances could have a significant effect on heat transfer across them. As in the Rijke tube, the disturbances occurring at a frequency corresponding to an acoustical resonance can be expected to be dominant. Therefore they would probably produce the most significant variations in the thickness of these layers, and hence the most significant variations in heat flux across these layers.

Merk's analysis presumed the existence of flow perturbations. That such perturbations can always be expected in nucleate and film boiling was shown by Schwartz and Siler¹¹. Their experiments demonstrated that for frequencies up to 700 cps, the sound emitted

for both nucleate and film pool boiling of water approached white noise.

Conclusions

Pressure oscillations accompanying forced convective heat transfer to initially liquid nitrogen and hydrogen have been shown to display properties of open-open pipe and Helmholtz resonance. Since a theoretical understanding exists for the analogous Rijke tube, which offers a simple geometry and an ideal gas for analytical simplifications, it is reasonable to assume that similar principles apply to the driving of acoustical oscillations in these experiments. Such oscillations should be anticipated whenever cryogenics are subject to forced convective heat transfer. However, the appearance of similar oscillations in experiments performed with two phase and supercritical water, supercritical RP-1, and gaseous hydrogen and helium at very high heat fluxes, indicate this phenomenon is not confined to cryogenics but requires the development of large radial gradients of physical properties.

NOTATION

A = cross-sectional flow area, in.²
 c = velocity of sound, in./sec
 L = length, in.
 m = mass of fluid in neck of resonator, slugs/12
 P = pressure, psia
 V_G = volume of gas in resonator cavity, in.²
 γ = ratio of specific heats
 ω_H = frequency of Helmholtz resonator, cps
 ω_p = fundamental frequency of open-open pipe resonance, cps

ACKNOWLEDGMENTS

This work has been undertaken as part of a doctoral dissertation for the University of New Mexico, Chairman of the dissertation committee is V. J. Skoglund; additional campus members are M. W. Wildin and G. A. Whan while the Los Alamos Scientific Laboratory advisors are J. D. Rogers and W. L. Sibbitt. The author is grateful to the cryogenics group, CMF-9, of the Los Alamos Scientific Laboratory for the instruction and assistance they provided in the use of their cryogenic facilities.

BIBLIOGRAPHY

1. Rijke, P. L., "Notiz ueber eine neue Art, die in einer an beiden Enden offenen Roehre enthaltene Luft in Schwingungen zu versetzen", Pogg. Ann., 107, 1859, 339-343.
2. McCarthy, J. R., and Wolf, H., "The Heat Transfer Characteristics of Gaseous Hydrogen and Helium", Rocketdyne Research Report RR-60-12, Canoga Park, California, December 1960.
3. Hines, W. S., and Wolf, H., "Pressure Oscillation Associated with Heat Transfer to Hydrocarbon Fluids at Supercritical Pressures and Temperatures", A.R.S. Jour., 32, 3, March 1962, 361-366.
4. Thurston, R. S., et al., "Cryogenic Fluids in Nuclear Propulsion Systems", LADC-5569, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, January 1963.
5. Goldmann, K., "Boiling Songs", NDA 10-68, May 1953.
6. Goldmann, K., "Heat Transfer to Supercritical Water at 5000 psi, Flowing at High Mass Rates through Round Tubes", Int. Devl. in Heat Transfer, ASME, 1961, 561-568.
7. "Nuclear Rocket Propulsion", NASA SP-20, 1962, 43-48.
8. Thurston, R. S., "Probing Experiments on Pressure Oscillations in Two Phase and Supercritical Hydrogen with Forced Convection Heat Transfer", Advances in Cryogenic Engineering, 9, Plenum Press, New York, 1965, 305.
9. Thurston, R. S., "Pressure Oscillations Induced by Forced Convective Heat Transfer to Two Phase and Supercritical Hydrogen Preliminary Experiments", LAMS-3070, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 1964.
10. Merk, H. J., "Analysis of Heat Driven Oscillations of Gas Flows, 1. General Considerations, 2. On the Mechanism of the Rijke-Tube Phenomena", App. Sci. Research, A6, 1957, 317-335, 402-420.
11. Schwartz, F. L., and Siler, L. G., "Correlation of Sound Generation and Heat Transfer in Boiling", ASME Paper 64-WA/HT-24, 1964.

CAPTIONS

Figure 1: Test Section Details

Figure 2: Pipe Resonance in Nitrogen.

Figure 3: Helmholtz Resonance in Nitrogen.

Figure 4: Superposition of Pipe and Helmholtz Resonance in Hydrogen.

Figure 5: Dependence of Pipe and Helmholtz Oscillations on Inlet Conditions.

SECTION A-A
 INLET PLENUM

SECTION B-B
 DURALUMINUM ROD
 WITH FLOW CHANNELS

SECTION C-C
 OUTLET PLENUM

NITROGEN EXPERIMENT OF SEPTEMBER 30, 1963
130 °R AT INLET, 160 °R AT OUTLET
8.15 in³ OUTLET PLENUM, 0.203 in. ORIFICE

FIGURE 2

NITROGEN EXPERIMENT OF OCTOBER 2, 1963
INLET TEMP SENSOR INOPERATIVE, 200°R AT OUTLET
27.9 in³ OUTLET PLENUM, 0.07 in. ORIFICE

NITROGEN EXPERIMENT OF OCTOBER 1, 1963
158°R AT INLET, 200°R AT OUTLET
8.15 in³ OUTLET PLENUM, 0.07 in. ORIFICE

FIGURE 3

HYDROGEN EXPERIMENT OF OCTOBER 14, 1963

FIGURE 4

PRESSURE, ATMOSPHERES

TEMPERATURE, °K

SUPERCRITICAL REGION

LOCUS OF SPECIFIC
HEAT MAXIMA

DOTS: OSCILLATIONS

CRITICAL POINT

CROSSES: NO OSCILLATIONS

SUBCRITICAL REGION

VAPOR PRESSURE LINE

(DENSE STATE)

(SUPER-
HEATED
STATE)