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THE INFLUENCE OF ULTRASONIC VIBRATIONS ON HEAT TRANSFER TO WATER FLOWING IN ANNULI*

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Abstract—An experimental study was conducted to determine the effects of high-intensity ultrasonic vibrations on heat transfer to water flowing in annuli. The inner tube of an annulus was electrically heated and cylindrical transducers were mounted on the outer tube to supply vibrational energy to the fluid in a direction normal to the heated surface. Heat transfer was improved with vibration to a degree dependent on the flow conditions and the extent of cavitation in the annular gap. The maximum local increase in heat-transfer coefficient of 40 per cent occurred with low flow velocities and high-heat-flux nonboiling conditions. Any vapor in the test section reduced the effect of vibration on heat transfer.

NOMENCLATURE

D, diameter;
D_e, hydraulic diameter;
E, voltage across transducers;
f, vibrational frequency;
h, heat-transfer coefficient;
I, vibrational intensity;
p, pressure;
q/A, heat flux;
T, temperature;
V, velocity;
x, distance along heated length;
μ, dynamic viscosity;
ρ, density;
Re, Reynolds number.

Subscripts
b, bulk fluid condition;
o, outer wall of annulus;
sat, saturation condition;
v, vibration;
w, heated surface.

If not specifically indicated, properties were evaluated at the bulk temperature of the fluid.

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INTRODUCTION

Numerous experiments have been performed in recent years to ascertain the effects of vibration on heat transfer. For most heat-transfer equipment, it is necessary to use the indirect approach whereby vibrations are applied to the fluid and focused towards the heated surface. Liquids exhibit a considerably more complex behavior than gases due to the possibility of cavitation and boiling.

Substantial improvements in nonboiling and boiling heat transfer have been observed when vibrations were applied to heated sections located in a large body of liquid. Gibbons and Houghton [1], Zhukauskas *et al.* [2], and Larson and London [3] noted several hundred per cent improvement in natural-convection heat-transfer coefficients. Isakoff [4] and Ornatskii and Shcherbakov [5] found that the critical heat flux for pool boiling of water was raised over 60 per cent. Low-frequency flow pulsations generated upstream were used by West and Taylor [6] and Lemlich and Armour [7] to improve coefficients for low velocity flow in tubes. Romie and Aronson [8] found no effect of upstream ultrasonic vibrations on subcooled critical heat flux for forced flow in annuli.

The few experiments in forced flow indicate that vibration has much less effect on channel flow than on natural-convection flow. However, with channel flow, the transducer has always been located outside the heated section with the result that the vibrational intensity was considerably attenuated. As a result it has not been clearly established whether intense, directly applied vibrations would significantly augment heat transfer in forced-convection channel flow. The objective of this investigation was to investigate this problem with an apparatus which permitted the application of transverse vibrations of high intensity to the fluid in the immediate vicinity of the heated surface.

EXPERIMENTAL PROCEDURE

A heat-transfer facility, providing moderate fluid flow rates at low pressures, direct-current generators for resistance heating, degassing and demineralizing equipment for water, and the requisite instrumentation, was used for this investigation. This system, located in the M.I.T. Heat Transfer Laboratory, is described in detail in [9].

Test-section assemblies were installed in the loop in the horizontal position. As shown in Fig. 1, each test section consisted of two concentric stainless-steel tubes providing an annular

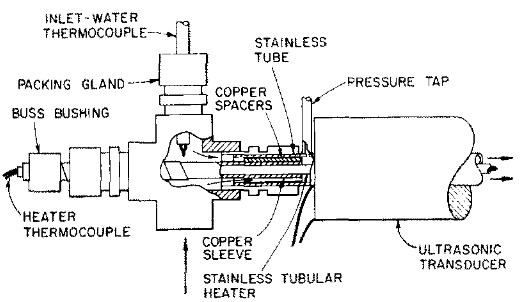

FIG. 1. Test-section assembly.

flow passage. Ultrasonic tranducers were mounted on the outer tube to supply vibrational energy to the fluid in a direction normal to the heated surface. The transducers were US500 elements developed by U.S. Sonics, Inc. Power for the transducer assembly was provided by a General Ultrasonics model GU400 ultrasonic generator.

Annuli of $D_e = 0{\cdot}122$ and $0{\cdot}178$ in ($D_o = 0{\cdot}242$ in for both) were used in combination with transducers having 70 and 80 kc principle, radial, resonant frequencies. Most tests were run with 100 V impressed across the transducers. Using the measured impedance of the transducers and an assumed efficiency of 30 per cent, the transmitted intensity at this voltage was estimated to be 1·4 W/cm^2. At this intensity audible cavitation was discernible for all test conditions.

For most runs the dissolved gas content was reduced from an equilibrium value of 12 cm^3/l. to less than 1 cm^3/l. as determined by the Winkler analysis. Test runs were made by increasing test-section power while maintaining constant inlet flow conditions. Data with the ultrasonic field were taken without altering either the flow conditions or heat flux of the accompanying reference run. In addition to the usual instrumentation, a traversing thermocouple was used to record the average local inner-wall temperature of the heated tube.

More detailed information relating to the experimental facility, test procedures, and data treatment is available in [10].

DISCUSSION OF EXPERIMENTAL RESULTS

Nonvibration data

Data were taken for a wide range of laminar and turbulent Reynolds numbers for both nonboiling and surface-boiling conditions. Typical axial profiles for nonboiling conditions are presented in Fig. 2. The end effects discernible in the profiles are due to the mounting arrangement which produced a sharp-edged inlet and exit. Average heat-transfer coefficients obtained by numerical integration were found to be in reasonable agreement with the predictions of Chen *et al.* [11] and Heaton *et al.* [12] for laminar flow and with the equation recommended by McAdams [13] for the turbulent region.

Typical wall-temperature profiles for surface-boiling conditions are depicted in Fig. 3. In the inlet region the heat-transfer coefficient is high enough to inhibit boiling, and as a result the usual entrance effects are present. As seen in Fig. 4 the data for fully developed boiling are in good agreement with data of McAdams [13] taken for similar heaters and flow conditions. The effects of gas content noted in Fig. 4 are also in agreement with the usual observations.

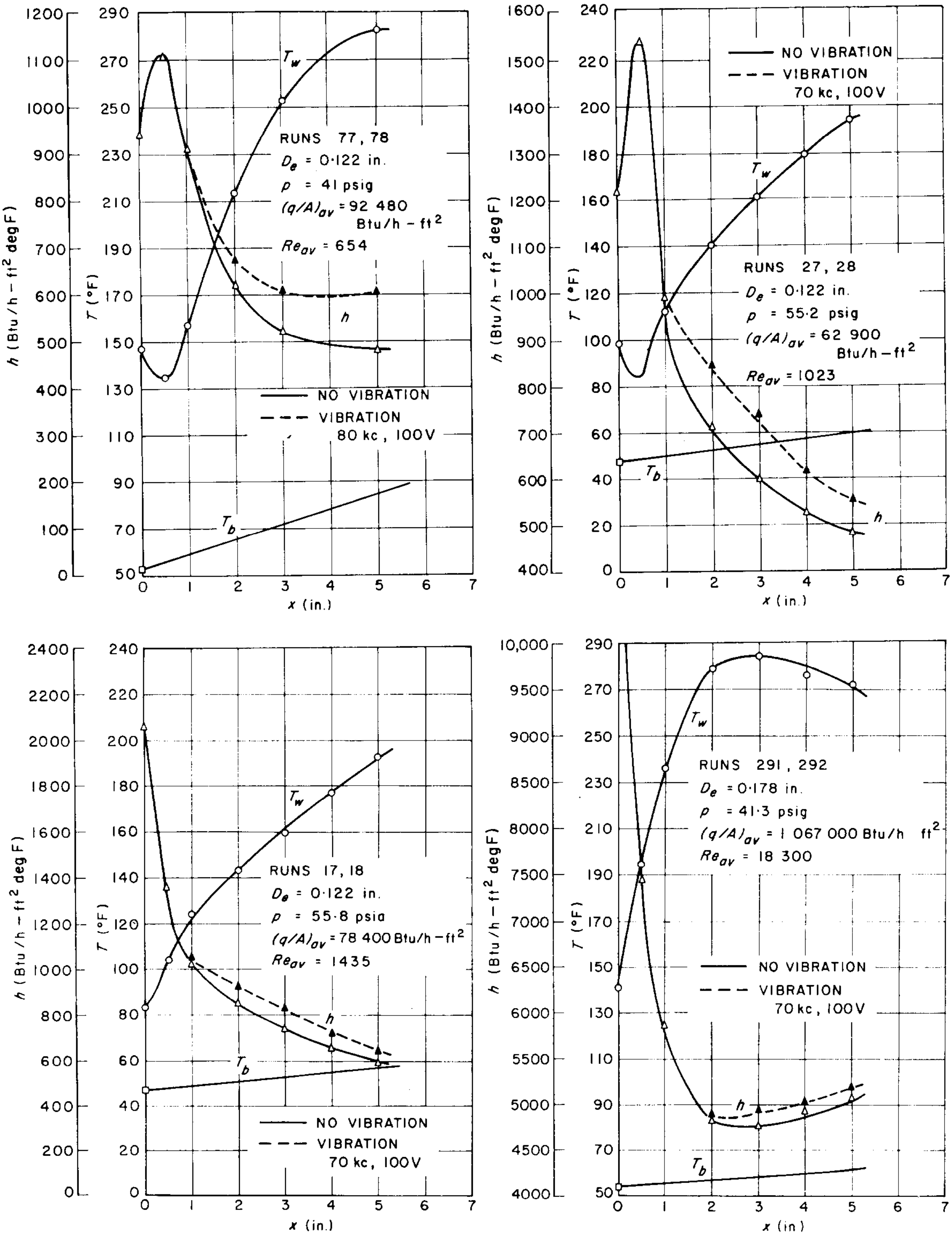

FIG. 2. Axial profiles exhibiting effect of vibration.

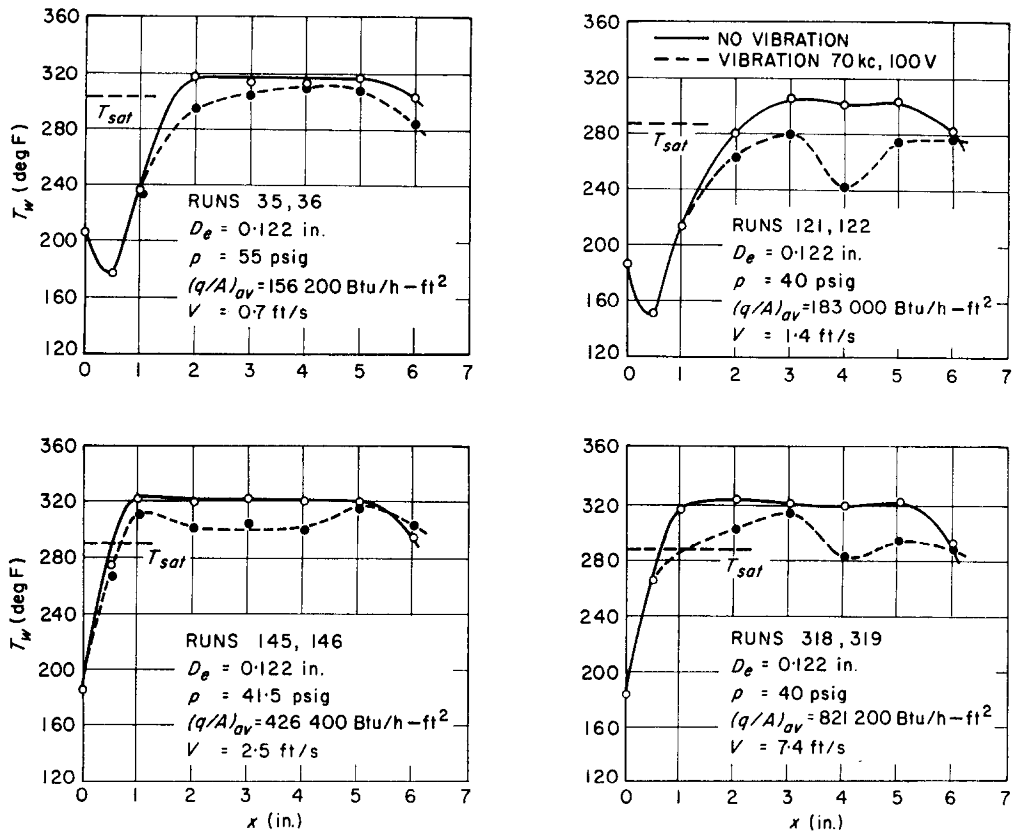

FIG. 3. Variation of surface temperature with axial position for boiling runs.

Critical heat-flux data were higher than observed by McAdams; however, this can be attributed to the improved system stability of the present tests.

It can be concluded, then, that these reproducible, nonboiling and boiling data provide an acceptable reference for the vibration studies.

Vibration data

The effects of ultrasonic vibration on heated-surface temperatures and heat-transfer coefficients are included in the previously discussed profile plots, Figs. 2 and 3. It is seen that the influence of a given vibrational intensity on heat transfer depends not only upon the heat flux and flow conditions, but also upon the annular dimensions and axial location. The effect of vibration on heat transfer can be conveniently represented by plotting both nonboiling and surface-boiling data in terms of heat flux vs. wall superheat. Figures 4 and 5 present local heat-transfer data for both equivalent-diameter test sections.

At wall temperatures low relative to the saturation temperature at the system pressure, the ultrasonic vibrations have little effect on heat transfer. However, at wall temperatures approaching the saturation temperature, heat-transfer coefficients are considerably increased by the vibration. The augmentative mechanism appears to be cavitation which agitates the thermal boundary layer in a manner similar to boiling. At the relatively low pressure used in these tests, cavitation occurred at and near the transducer surface with the result that there was considerable attenuation of the sound intensity

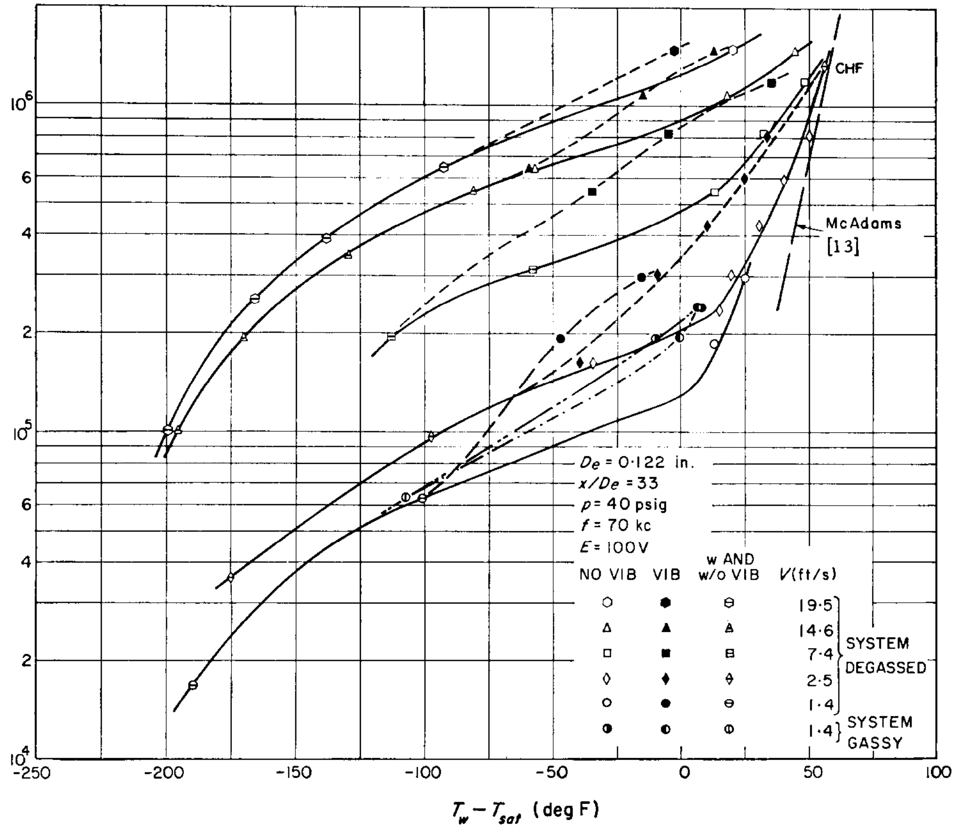

FIG. 4. Influence of ultrasonic vibration on heat transfer under nonboiling and boiling conditions; $D_e = 0{\cdot}122$ in, $x/D_e = 33$.

in the annular gap. Accordingly, high heated-surface temperatures were required for cavitation to occur at the heated surface.

As expected, the vibrational effect is most significant at the lower flow velocities where the agitation due to cavitation is substantial compared to the normal convective effect. The effect of the vibrational field also diminishes as surface boiling becomes well established. This would appear to be due to the dominance of the bubble agitation as well as the increased attenuation and scattering caused by the higher vapor densities.

Numerous tests indicated no appreciable change in the critical heat flux when the vibrator was activated. This follows from the fully developed boiling results since the coalescing bubbles at the critical condition would be expected to be even more of an impediment to the transfer of vibrational energy. It is not surprising that Romie and Aronson [8] also found negligible effect of ultrasonic vibration on the critical heat flux. Their upstream vibrations would have been subject to much more attenuation than the present arrangement. In addition, mere breaking up of the bubble boundary layer by the vibration would not be sufficient unless the vapor could be pushed out into the main stream so that it could condense. Pool boiling, on the other hand, would seem to be more conducive to augmentation by vibration since the bubbles can be readily dislodged into the pool.

The effect of vibration was diminished when the system was not degassed (Fig. 4, $V = 1{\cdot}4$ ft/s). Decreases in heat-transfer coefficient with vibration were even noted. This effect can probably be

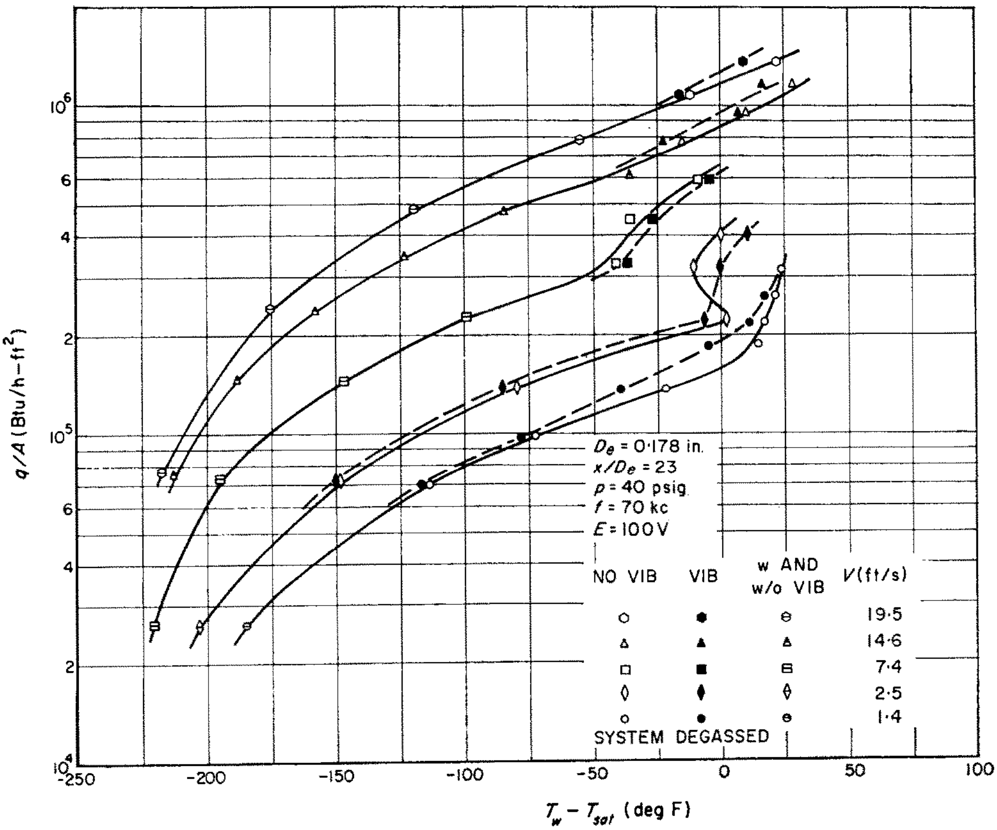

FIG. 5. Influence of ultrasonic vibration on heat transfer under nonboiling and boiling conditions; $D_e = 0{\cdot}178$ in, $x/D_e = 23$.

attributed to the acoustic degassing caused by the high-intensity vibrational field. The intensity is sharply attenuated by the gas which has come out of solution.

In general there was less improvement in heat transfer with the larger annulus. This is due primarily to the greater attenuation with total cavitation which overrides the focusing effect.

Considerable axial variation in the effect of vibration on heat transfer was also observed. The axial profile plots show that there is very little effect of vibration discernible in the inlet region. This is probably due to the high heat-transfer coefficients which are normally present there.

At pressures of about 70 psia, the difference between the system pressure and the vapor pressure at the vibration source temperature ($\sim$ fluid temperature) was sufficiently above the amplitude of the ultrasonic pressure wave to inhibit cavitation at the vibration source. However, due to the radial focusing and higher equilibrium vapor pressure at the heated surface, cavitation occurred there. The consequences of this change in cavitation conditions are illustrated in Fig. 6 where data for several pressures are compared. At the highest pressure, vibration produced an increase in the heat-transfer coefficient with an appreciably subcooled surface. The maximum improvement in heat transfer was about the same as for the low pressure case where cavitation occurred throughout the annular gap.

Effects of acoustic variables

The results discussed above were obtained

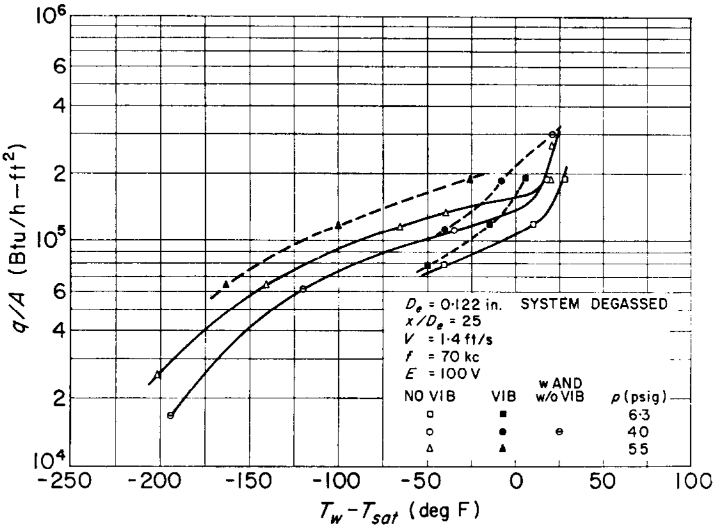

FIG. 6. Effect of system pressure on influence of ultrasonic vibration on heat transfer.

with constant power input to the ultrasonic transducer, or equivalently, constant vibrational intensity. The effect of intensity on the heat-transfer coefficient is shown in Fig. 7 for a typical nonboiling case. Improvement in heat transfer was first noted at 0·23 W/cm² which also corresponded to the onset of audible cavitation. This is a relatively low intensity and cavitation probably occurred only near the heated surface. With increasing intensity the cavitation spread throughout the annular gap. The intensity at the heated surface is then attenuated as evidenced by the decreasing slope of the curve.

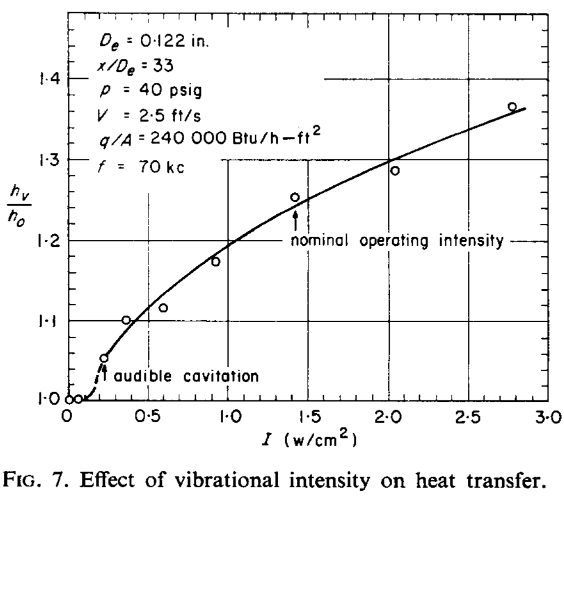

FIG. 7. Effect of vibrational intensity on heat transfer.

Data were also taken with an 80-kc transducer assembly for a wide range of flow conditions. Since no significant change in the effect of vibration on heat transfer was observed with this unit, the present discussion has been concerned with the more extensive results for the 70-kc transducer. However, frequency as well as intensity should be considered as important variables in future studies on this subject.

Magnitude of improvement in heat transfer

The maximum local increase in heat-transfer coefficient was approximately 40 per cent. The maximum average increase was only about 10 per cent since the heat-transfer mechanism was not enhanced in the entrance region. This average improvement would be substantially greater for longer channels where the entrance region does not occupy such a large fraction of the channel.

These results indicate that improvements in heat transfer are modest when high intensity vibrations are applied to forced flow in channels. Even when the transducer is placed in close proximity to the heated surface, the vibrational intensity is seriously attenuated by any vapor existing in the fluid. It is immaterial whether this vapor results from boiling, dissolved-gas evolution, or cavitation. It appears that practical application of fluid vibration will be limited to pool conditions where the convective conditions are more suited to augmentation by vibration.

REFERENCES

1. J. H. GIBBONS and G. HOUGHTON, Effects of sonic vibrations on boiling, *Chem. Engng Sci.* **15**, 146–148 (1961).
2. A. A. ZHUKAUSKAS *et al.*, Investigation of the influence of ultrasonics on heat exchange between bodies in liquids, *J. Engng Phys.* **4**, 58–60 (1961).
3. M. B. LARSON and A. L. LONDON, A study of the effects of ultrasonic vibrations on convection heat transfer to liquids, ASME Paper No. 62-*HT*-44 (1962).
4. S. E. ISAKOFF, effect of an ultrasonic field on boiling heat transfer—exploratory investigation, Heat Transfer and Fluid Mechanics Institute Preprints, Stanford University, 16–28 (1956).
5. A. P. ORNATSKII and V. K. SHCHERBAKOV, Intensification of heat transfer in the critical region with the aid of ultrasonics, *Teploenergetika*, **6**, (1) 84–85 (1959).
6. F. B. WEST and A. T. TAYLOR, The effect of pulsations on heat transfer, *Chem. Engng Progr.* **48**, 39–43 (1962).
7. R. LEMLICH and J. C. ARMOUR, Forced convection heat transfer to a pulsed liquid, Amer. Inst. Chem. Engrs. Preprint No. 2 for Sixth National Heat Transfer Conference, August (1963).
8. F. E. ROMIE and C. A. ARONSON, Experimental investigation of the effects of ultrasonic vibrations on burnout heat flux to boiling water, *ATL-A*-123, July (1961).
9. A. E. BERGLES and W. M. ROHSENOW, The determination of forced-convection surface-boiling heat transfer, *J. Heat Transfer* **86**, 365–372 (1964).
10. P. H. NEWELL JR., The effect of ultrasonic vibration on forced convection heat transfer, Mech. E. Thesis, Department of Mechanical Engineering, M.I.T., June (1964).
11. C. Y. CHEN, G. A. HAWKINS and H. L. SOLBERG, Heat transfer in annuli, *Trans. Amer. Soc. Mech. Engrs* **68**, 99–106 (1946).
12. H. S. HEATON, W. C. REYNOLDS and W. M. KAYS, Heat transfer in annular passages. Simultaneous development of velocity and temperature fields in laminar flow, *Int. J. Heat Mass Transfer* **7**, 763–781 (1964).
13. W. H. MCADAMS, *Heat Transmission*, 3rd ed. McGraw-Hill, New York (1954).

Résumé—Une étude expérimentale a été menée pour déterminer les effets des vibrations ultrasonores à intensité élevée sur le transport de chaleur à partir d'eau s'écoulant dans une conduite annulaire. Le tube intérieur d'une telle conduite était chauffé électriquement et des transducteurs cylindriques étaient montés sur le tube extérieur pour fournir de l'énergie de vibration au fluide dans une direction normale à la surface chauffée. Le transport de chaleur était amélioré par la vibration d'une quantité dépendant des conditions de l'écoulement et de l'étendue de la cavitation dans l'espace annulaire. L'augmentation locale maximale de 40 pour cent du coefficient de transport de chaleur se produisait avec des vitesses d'écoulement faibles et des conditions de flux de chaleur élevé mais sans ébullition. Toute présence de vapeur dans la section d'essai réduisait l'effet de la vibration sur le transfert de chaleur.

Zusammenfassung—Um die Auswirkung von Ultraschallschwingungen hoher Intensität auf den Wärmeübergang an Wasser, das in Ringspalten strömt, zu bestimmen, wurde eine experimentelle Arbeit durchgeführt. Das Innenrohr des Ringspaltes wurde elektrisch beheizt und auf das Aussenrohr wurden zylindrische Übertrager aufgebracht, um die Schwingungsenergie an die Flüssigkeit in einer Richtung senkrecht zur beheizten Oberfläche heranzubringen. Der Wärmeübergang wurde durch Schwingung bis zu einem Grad verbessert, der von den Strömungszuständen und der Grösse der Hohlraumbildung im Ringspalt abhing. Der maximale lokale Anstieg der Wärmeübergangszahl von 40% trat bei geringen Strömungsgeschwindigkeiten und hohen Wärmestromdichten bei Nicht-Sieden auf. Dampf in der Versuchsstrecke verminderte den Einfluss von Schwingungen auf den Wärmeübergang.

Аннотация—Проведены эксперименты с целью определения влияния высокоинтенсивных ультразвуковых колебаний на перенос тепла при течении воды в каналах. Внутренняя труба в канале нагревалась электрическим током, а на наружной трубе монтировались цилиндрические преобразователи для подачи энергии колебаний к жидкости по нормали к поверхности нагрева. При вибрации величина переноса тепла возрастала до значения, зависящего от условий течения и размеров кавитации в кольцевом зазоре. Локальный коэффициент теплообмена увеличивался максимум на 40% при малых значениях скорости течения и больших тепловых нагрузках при отсутствии кипения. Присутствие пара в рабочем участке снижало влияние вибрации на перенос тепла.