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MASTER

HEAT TRANSFER IN OSCILLATING FLOW

Second Progress Report

For the Period 1 October 1959 to 30 September 1960

Aeronautical Engineering Report No. 483-b

PRINCETON UNIVERSITY
DEPARTMENT OF AERONAUTICAL ENGINEERING

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NOMENCLATURE

- $\tilde{p}$ = local unsteady component of pressure, peak-to-peak amplitude
 $\tilde{p}_0$ = $\tilde{p}$ as measured at the downstream duct end (siren end) normally a point of maximum
 $\bar{p}_0$ = steady-state reference pressure, the static pressure as measured at the downstream end of the duct.
 q = local total heat flux, which includes the steady-state and unsteady components ($q = \bar{q} + \tilde{q}$). Since in the tests described heat strip power is fixed, this quantity stays constant.
 $\bar{q}$ = steady-state heat flux, measured at the heater strip with the same static pressure and mass flow as was present under oscillating conditions.
 $\tilde{q}$ = unsteady component of heat flux
 x = distance from siren (downstream) end of the duct
 L = duct length (83.44 inches, acoustic length)

I. SUMMARY

The investigation of heat transfer in oscillating flow has continued to yield pertinent information as to the heat transfer increases possible as well as the effect of certain parameters on the changes observed.

Using a resonating duct, peak-to-peak amplitudes as high as .5 of the steady-state pressure have been produced. The steepening of the waves into a "shock-type" form partially accounts for the pressure amplitudes recorded. Such oscillations have produced heat transfer increases as high as three times the steady-state values. The increases were shown to be dependent on the proximity to the velocity antinode locations in the duct, with minimum increases occurring at the velocity nodes.

A series of tests to further investigate the dependence of heat transfer on various parameters were made for three locations of the heat transfer section along the duct at several harmonic frequencies with pressure amplitudes (velocity amplitudes have yet to be measured directly) varying from .4 steady-state pressure to zero. The data from these tests at 120 cps indicate a shift in the pressure amplitude envelope in the upstream direction. From the limited data available the maximum heat transfer was seen to occur close to the velocity antinode location.

When the heat transfer increase to steady-state heat transfer ratio was plotted versus the ratio of peak-to-peak pressure amplitude to steady-state pressure (measured at the downstream end of the duct), the following relationship was found:

$$\tilde{q}/\bar{q} = K (\tilde{P}_0/\bar{P}_0)^{1.4}$$

where $0.1 \leq P_0/P \leq 0.3$ and $\bar{P}_0 \approx 200$ psia, and K for this case = 11.7.

Data obtained at 120 cps and 200 cps indicated the same relationship between pressure amplitude (representing local velocity) and heat transfer.

A complete survey to cover the entire heat transfer profile is underway and until that data becomes available these results must be considered preliminary.

II. INTRODUCTION

A. Object

In the case of excessive heat transfer associated with both liquid and solid propellant rocket motors experiencing combustion instability (and in the opposite case where it would be desirable to increase heat transfer such as in gaseous cooled nuclear reactors), the ability to understand the phenomenon of heat transfer with oscillating flow is of major importance. With rocket motor heat transfer, it was necessary to determine whether the increase was due to chemical effects associated with the combustion or whether the increase could be shown to be a function of the flow characteristics alone.

The problem from a theoretical standpoint is extremely difficult and in the light of present knowledge remains unsolved. The approach of this investigation is to isolate the various important parameters and determine their relationship to the heat transfer rates observed. With this data as a background one might hopefully obtain a theoretical solution of the problem, however, it is quite possible that the engineering solution based on dimensional analysis and experimental values will constitute the ultimate result.

B. History

This research program concerning the effect of oscillating flow on heat transfer has been in progress since 1 July 1958 under sponsorship of the Power Branch, Office of Naval Research.

The first experimental work was carried out in a nonresonating variable-length duct with fully-developed pipe flow present. Heat transfer was from an electrically heated ribbon of nichrome set in the duct walls to the flowing room temperature air. Extensive tests covering a wide range of frequencies resulted in heat transfer increases up to 70% above the measured heat transfer (within 5% of calculated) under steady-state conditions. Heat transfer was found to be sensitive to amplitude and frequency of oscillation for low Mach number flow (.026), but the dependence upon these parameters appeared to decrease as the Mach number increased (the highest value reached in those tests was .1). The pressure transducer records indicated that sufficient travel time was allowed for the waves to steepen considerably prior to reaching the heater section.

III. EXPERIMENTAL APPARATUS

A. Wave Generator, Heater Unit

In general, the experimental apparatus may be described as consisting of a variable length, $1\frac{1}{2}$ inch diameter duct terminating in a rectangular orifice. The orifice is opened and closed periodically by a revolving disc having between 2 and 28 openings and capable of generating pulsations covering a frequency range from 50 to 10,000 cps. Heat is supplied to the flowing gases from an electrically heated nichrome ribbon set in the duct wall and capable of being moved to various locations. A complete description of the experimental apparatus was presented in Reference 1. The description here will be limited to more recent improvements and design changes now in progress.

In addition to the ability to vary the frequency of the generated pressure wave, the ability to vary amplitude is seen to be of equal importance. If the wave shapes produced are sinusoidal, use of the resonance characteristics of the tube allows a variation in amplitude with small changes in frequencies

and little or no change in wave shape (Reference 2). However, different problems are present when working in a duct in which travel times have been designed such as to allow the waves to steepen into shock or near shock-type waves. Wave shape characteristics at various duct locations have been shown to drastically change with small frequency variations. Thus, any changes in amplitude must be accomplished without altering the frequency.

It was with these factors in mind that the mechanism to vary the intra-orifice gap (that space between the fixed rectangular orifice at the end of the duct and the revolving orifice) was developed. Since it was desirable to vary the intra-orifice gap under flow and heat transfer conditions, the mechanism was designed for remote operation using a reversible-drive motor. A photograph of the completed installation is shown in Figure 1.

Experimental utilization of this device consisted of first obtaining the minimum intra-orifice gap under operating conditions. Since there is a certain amount of dynamic loading on the revolving orifice, the gap dimensions must be determined during operation if destructive contact between fixed and revolving orifice is to be avoided. The method used consisted of electrically isolating the revolving orifice from the remainder of the apparatus. Using an oscilloscope and a low voltage source, the intra-orifice gap was reduced to the condition where light surface contact was present indicated by intermittent oscilloscope pips. This represented the condition for maximum amplitude when a resonance condition for maximum amplitude when a resonance condition was accurately attained.

Maintaining the frequency constant the gap was opened in steps of approximately 20% of maximum peak-to-peak pressure amplitude. These steps were determined on a vacuum tube voltmeter. Occasionally small adjustments of the frequency were necessary. These were accomplished using precise frequency measurements (within $\pm .1$ cps) on the Berkeley counter. To provide an accurate

signal: from which to count, a pass band filter was used to eliminate extraneous signals. Changes of only a few tenths of a cycle resulted in noticeable changes in the wave shape and amplitude as displayed on the meters and oscilloscopes. Mass flow remained constant throughout the intra-orifice gap variations through the use of an upstream sonic orifice.

B. Instrumentation

Improvements in the cutoff characteristics of the filters associated with the pressure transducers has constituted one active area of instrumentation improvement. Since shock-type waves require gages with high frequency response to faithfully reproduce the wave shape, future testing will concentrate on crystal gages (natural frequency = (0) 160 kc) as the "standard."

The thermocouple measurements of the heater strip temperature have been further improved. The use of Sauereisen cement and periodically polishing the outside of the nichrome heater strip has eliminated the problem of surface oxidation due to the air flow past these points. Agreement between the thermocouples (3 at 120° intervals) has been of the order of a few percent. A ceramic-bonded resistance thermometer which is attached directly to the heater strip will be used on the revised apparatus described elsewhere in this report. An area will be measured by this method and average temperature can be recorded directly.

Another area of active interest includes the development of electronic gage which could provide a better measurement of amplitude when dealing with various wave shapes.

Some effort has also been expended in simulating the wave shapes electronically as a means to better analyze the wave shapes recorded in various duct locations. Unfortunately to date, this approach to the analysis of the "wave shape effect" has met with only limited success.

IV. EXPERIMENTAL PROGRESS

The first series of experiments undertaken during this report period were to determine whether or not the experimental apparatus was capable of producing the magnitude of heat transfer increases observed when oscillations occurred in the presence of combustion (References 3 to 5). When nonresonance conditions were produced in the duct, heat transfer increases were limited to approximately 70% (Reference 1).

With the entrance screens removed resonance conditions could be readily produced. Figure 2 illustrates this fact and points out another interesting aspect of oscillating flow. That is, when the static pressure as measured at the upstream or downstream end of the tube is used as a reference, shifting in the amplitude ratio curves occurs at lower frequencies (in this case, 120 cps and below) and at the resonant peaks. The downstream end static pressure will be used as the standard for comparisons in this report.

With resonance, it was immediately apparent that heat transfer increases of several hundred percent could be attained. In Figure 3 some of the first data obtained illustrate the 215% increase in heat transfer above steady-state conditions for the seventh harmonic (frequency $\approx$ 290 cps). A number of additional tests were made and heat transfer increases of up to 300% were regularly produced.

Referring again to Figure 3, it would first appear that the heat transfer increased for the higher harmonics. However, since the heater section was located at a fixed position (in this case at the center location on the duct) for each of these harmonics, it is interesting to compare the distance from the heater strip to the theoretical location of the nearest pressure nodal point (point of maximum velocity). These distances were 14, 8.4 and 5.9 inches for the third, fifth and seventh harmonics indicating an increase in heat transfer as the location of the velocity antinode was approached.

Naturally, in this type of experiment only tentative conclusions could be drawn. However, the tests illustrated in Figure 3 and other similar data pointed out the need for a series of tests to be made in which the heater section was moved to various duct locations in order that the effect of the unsteady component of velocity might be checked out more thoroughly.

With this preliminary data in mind, a series of tests was initiated which provided for movement of the heater section to three locations. At each location the duct was operated at 5 harmonic frequencies (harmonics 3, 5, 7, 9 and 11 for the 40 cps fundamental). This allowed several parameters to be investigated simultaneously.

Early in the testing, it was evident that the resonant conditions in a duct for steepened waves was significantly different from those obtained with sinusoidal waves. For example, even square waves could be produced at some locations with slight alteration in the frequencies. For this reason it was necessary to closely control the resonance frequencies as is discussed in the experimental apparatus section.

In Figure 4 (for the third harmonic) the data of pressure amplitude and heat transfer are presented as gathered from the three heater section locations along the duct. These locations are indicated as A, B and C and are the same for all the harmonic tests. The nondimensionalized pressure data when compared to the expected pressure mode distributions indicate that the pressure amplitude envelope is distorted on the upstream side. This shift is very evident for the third harmonic. A certain amount of scatter in the points is present but is to be expected from the wave shape differences due to small frequency differences between tests at the three locations and the three pressure amplitude levels shown. The data taken at the three pressure levels indicate a random scatter about the same normalized pressure values.

The heat transfer increase was found to reach its highest value in the vicinity of the antinode (pressure nodal point). With only three data points, only tentative conclusions can be drawn as to the heat transfer profile along the duct (or over a wavelength). Further testing will be required to accurately determine this profile. Under constant frequency conditions, it is planned to move the test section in small increments along the duct length with velocity profile surveys conducted at each location. Pressure and velocity measurements will be made at the exact location of heat input, since as Figure 4 indicates it is not possible to predict conditions with sufficient accuracy from downstream locations.

Figure 5 indicates similar results for the fifth harmonic where the pressure amplitude envelope agrees more closely to the predicted amplitudes. Peaking of the heat transfer again is in the vicinity of the velocity maximum region as well as at another downstream location, but again a great number of additional heat transfer locations are necessary to make any accurate determination. The frequency variation scatter should be eliminated in the revised apparatus, since the frequency can remain fixed.

While the data just described still leave a great deal to be desired, some extremely interesting information can be derived from these tests. If we plot the ratio of the local increase in heat transfer rate evaluated in the region close to the velocity maximum over the steady-state heat transfer rate versus the amplitude of the peak-to-peak pressure over the steady-state pressure, we obtain the results shown in Figure 6. These data are plotted for values of $\tilde{P}_0/\bar{P}_0$ between .1 and .3 and steady-state pressure 200 psia nominal. For the third and fifth harmonics, representing frequencies of 120 cps and 180 cps, agreement is good. Using a straight-line relationship on the log-log plot of Figure 6 results in the following:

$$\tilde{q}/\bar{q} = K (\tilde{P}_0/\bar{P}_0)^{1.4}$$

where $K = 11.7$ for this case

The higher harmonics (seventh through eleventh, 280 to 440 cps), although indicating close agreement as far as the pressure exponent was concerned, provided different values of K . This, of course, is to be expected. In fact, if one uses Figures 4 and 5 as a reference, it would appear that coincidence was a major influence in providing the same K factor for the third and fifth harmonics. The solution to the problem of finite size and limited number of locations of the heater section, which causes difficulties in the prediction of the exact location of maximum heat transfer, lies in the complete survey technique which is employed in the revised experimental apparatus.

Again it is pointed out that what is related here is the heat transfer changes in the vicinity of the velocity antinode as compared to the pressure fluctuations as measured at the tube end (pressure antinode). The reason for such a comparison being that no direct relationship could be established between the heat transfer and the local velocity fluctuations, since the velocity has yet to be measured directly in this apparatus. Preparations for these tests are underway at this time. Additional information on the nonlinear pressure-velocity relationship will be obtained in the planned tests as well as evaluations of transport properties under oscillating conditions.

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Intra-orifice gap drive

Figure 1

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Low frequency range duct resonance characteristics

Upstream pressure -----Δ-----
Downstream pressure —○—

Figure 2

Figure 4
 Normalized unsteady pressure $\sim \frac{\tilde{p}_{\text{peak-to-peak local}}}{\tilde{p}_{\text{peak-to-peak (siren end)}}}$

Unsteady heat transfer ratio $\sim \frac{\tilde{q}_{\text{unsteady}}}{\bar{q}_{\text{steady-state}}}$

Figure 5
 Normalized unsteady pressure $\frac{\tilde{p}}{\bar{p}}$ peak-to-peak (siren end)
 $\frac{\tilde{p}}{\bar{p}}$ peak-to-peak (siren end)