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TEMPERATURE SEPARATION PRODUCED BY A HARTMANN–SPRENGER TUBE COUPLING A SECONDARY RESONATOR

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Abstract — Temperature separation of a gas is produced by the Hartmann–Sprenger (HS) tube worked by jet flow issuing from a convergent nozzle. The effect of temperature separation depends on thermal effects of the HS tube.

The coupling of a secondary resonator to the HS tube or the use of a convergent nozzle with thin rod laid along its axis changes operation mode of the HS tube, and these can improve strength of oscillation in the HS tube and the thermal effect of it.

In the present paper, effects of the secondary resonator and of the use of the nozzle with rod on the thermal effects are observed. Considering these effects, an apparatus of temperature separation is composed, and its separation characteristics are investigated for various operation modes of the HS tube and for various sizes of hot-gas outlet.

From experimental results, optimum operation mode and optimum size of hot-gas outlet for the efficiency of temperature separation are found.

NOMENCLATURE

d, diameter of thin rod laid along convergent nozzle axis [mm];
D_H, diameter of hot-gas outlet [mm];
D_N, diameter of nozzle exit [mm];
D_S, inner diameter of secondary resonator (diameter of cold-gas outlet) [mm];
D_T, inner diameter of HS tube [mm];
f, frequency of air column oscillation in HS tube coupled secondary resonator [Hz];
f_0, frequency of air column oscillation in HS tube without secondary resonator [Hz];
G_c, mass of cold gas [kg/s];
G_H, mass of hot gas [kg/s];
G_N, mass of total gas issuing from nozzle [kg/s];
l, spacing between nozzle exit and entrance of HS tube [mm];
L_S, length of secondary resonator [mm];
L_T, length of HS tube [mm];
p, pressure [Pa];
p_H, pressure in collection chamber of hot gas [Pa];
p_{IN}, pressure of nozzle inlet [Pa];
p_∞, pressure of nozzle exit [Pa];
S_H, cross-sectional area of hot-gas outlet [mm^2];
S_T, cross-sectional area of HS tube [mm^2];
t, time [s];
T, temperature [K];
T_C, temperature of cold gas [K];
T_H, temperature of hot gas [K];
T_{IN}, temperature of nozzle inlet [K];
T_W, temperature of tube wall [K];
ΔT_{ad}, adiabatic temperature drop $\left\{= T_{IN}\left[1-\left(\frac{p_\infty}{p_{IN}}\right)^{(\gamma-1)/\gamma}\right]\right\}$ [K];
x, axial coordinate of HS tube [mm];
X, non-dimensional form of axial coordinate ($= x/L_T$).

Greek symbols

γ, ratio of specific heats;
ξ, fraction of hot gas $\{= G_H/G_N\}$;
η, efficiency of temperature separation defined by equation (2) [%];
Θ, non-dimensional form of temperature defined by equation (1);
Θ_C, Θ_H, non-dimensional forms of cold-gas and hot-gas temperatures respectively;
Θ_W, non-dimensional form of wall temperature of HS tube;
τ, non-dimensional form of time ($a_{IN} \cdot t/L_T$) (where a_{IN} is sound velocity at nozzle inlet).

1. INTRODUCTION

THE GAS column in the Hartmann–Sprenger (HS) tube (often called the resonance tube) driven by jet flow is excited to a finite amplitude oscillation accompanying travelling shock waves. The gas near the closed end of the HS tube is heated to a very high temperature. This phenomenon is called "the thermal effect of the HS tube", and was observed by Sprenger in 1954 [1]. In his report, the temperature separation effect was shown briefly as an application of the thermal effect and was compared with the separation effect of Hilsch's vortextube. Experimental results obtained by Sprenger show that the temperature of hot gas is very high at a small fraction of it, and the cooling effect of the HS tube is inferior to Hilsch's tube.

A phenomenon of the temperature separation produced by the HS tube is as follows: compressed gas issuing from a nozzle and entering into the HS tube is separated into cold gas issuing from the open end of the tube and hot gas discharging through a tiny orifice (hot-gas outlet) bored at the end wall of the tube. The orifice affects the flow in the HS tube. Frequency and amplitude of oscillation in the HS tube decrease as the orifice size increases. The HS tube, however, is worked up to $S_H/S_T \simeq 0.3$ in the case of operations by under-expanded jet flows, and the temperature separation is produced by it.

The temperature separation produced by the HS tube is caused by its thermal effect which is due to cumulative heat addition to the trapped end-wall gas by dissipative processes across shock waves propagating in the HS tube and also wall friction. Systematic investigations on the thermal effect were performed by some researchers. Brocher and Maresca [2] observed the thermal effect for various values of Mach number of jet flows and for some kinds of tube materials and operational gases. The authors [3] presented numerical calculations on processes of temperature rise and on maximum temperature in the HS tube for different tube materials. Sarohia and Back [4] systematically investigated relations between operational modes of the HS tube and its thermal effects. There are few investigations on developing the thermal effect. McAlvey and Pablak [5] observed flows in the tapered HS tube and suggested improvement of the thermal effect in it. Marcese and Racowsky [6] studied the ignition system of a rocket motor using the HS tube, and showed that the stepped tube was superior to the cylindrical tube in both maximum temperature and minimum time to achieve maximum temperature.

The authors showed acoustic phenomena of the HS tube coupling a secondary resonator [7]. The changes of operation mode of the HS tube by the coupling affect the thermal effect. If the ratio of lengths of the secondary resonator and the HS tube is set properly, the thermal effect can be improved.

A convergent nozzle with thin rod laid along its axis is used for subsonic operation of the HS tube. The use of the nozzle with rod brings about an increase in oscillation amplitude in the HS tube worked by under-expanded jet flow, and this also results in improvement of the thermal effect.

In the present paper, the effects of the secondary resonator and of the use of the nozzle with rod on the thermal effect are observed. Considering these effects, an apparatus of temperature separation is composed, its separation characteristics worked by air-jet flows are investigated for various operation modes (at different nozzle pressure ratios) and for various sizes of hot-gas outlets which are bored into centre of the end wall of the tube.

2. EFFECTS OF SECONDARY RESONATOR

When the HS tube is used as a sound generator, i.e. the Hartmann generator, a secondary resonator is often coupled with the aim of developing a powerful generator. In this section, effects of the secondary resonator on the thermal effect of the HS tube are observed.

2.1. *Experimental apparatus*

Experimental apparatus is shown in Fig. 1. A cylindrical secondary resonator is coupled to the HS tube. Its length is varied by a piston across $L_S/L_T = 1$. Spacing between the nozzle exit and the entrance of the HS tube is also variable.

Pressure histories in the HS tube and the end wall temperature are measured with pressure transducer of semi-conductor type and chromel–alumel thermocouple, respectively. Oscillation frequency of the tube is given by fundamental frequency of pressure fluctuation in the HS tube. Shock structures appeared in jet flow between the nozzle exit and the entrance of the HS tube are observed visually by the Schrielen method.

The HS tube is worked by air-jet flow issuing from the convergent nozzle. Flow in the secondary resonator is pulsated in frequency of periodic inflow and outflow at the entrance of the HS tube.

2.2. *Experimental results and considerations*

Figure 2 shows the dependency of the secondary resonator length on oscillation frequency and on end wall temperature in the HS tube, where non-dimensional form of temperature Θ is defined by

$$\Theta = 1 + \frac{T - T_{IN}}{\Delta T_{ad}} \tag{1}$$

and Θ_{W0} is the non-dimensional form of maximum end wall temperature obtained in the case that the HS tube without the secondary resonator is worked under

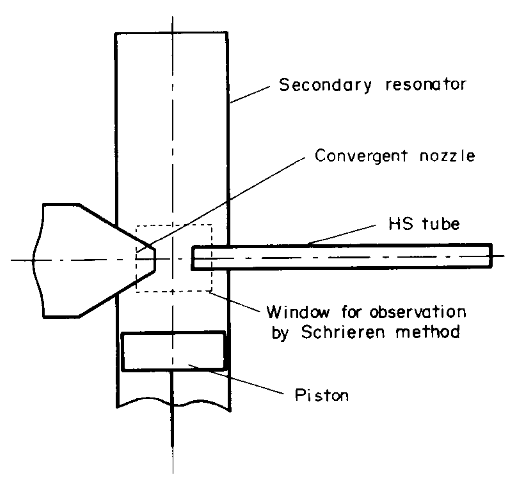

FIG. 1. Geometric configuration of HS tube coupling secondary resonator.

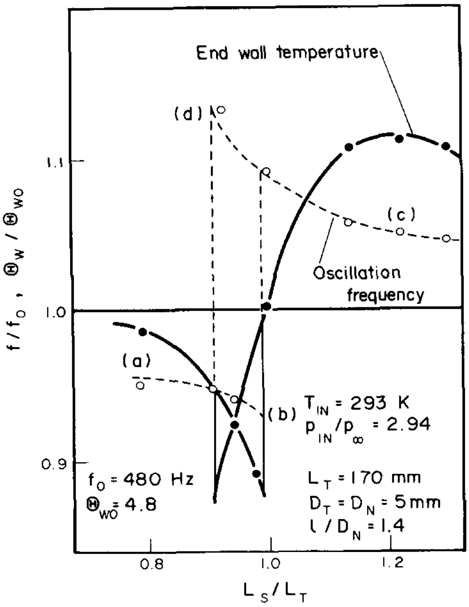

FIG. 2. Effects of secondary resonator length on oscillation frequency and end wall temperature.

the same nozzle pressure ratio. And f_0 is frequency in that case.

In the region of $L_S/L_T < 1$, oscillation frequency decreases as the secondary resonator length increases. When L_S/L_T is nearly equal to 1, the frequency jumps abruptly to a level higher than one. After the frequency jump, the frequency decreases again as L_S/L_T increases. When L_S/L_T is reduced reversely, change of the frequency follows along same path. However, the position of the frequency jump is different. Consequently, a hysteresis loop of frequency change is formed. Flow in the HS tube changes with this hysteresis phenomenon of frequency, and it influences the thermal effect.

While the end wall temperature remarkably decreases just before frequency jumps, Θ_W/Θ_{W0} in the region of $L_S/L_T > 1$ itself becomes greater than 1. It decreases again as the secondary resonator length increases, because a second hysteresis loop appears near $L_S/L_T \simeq 3$.

The hysteresis phenomena of oscillation frequency of the HS tube coupling the secondary resonator have been investigated by the authors and others [7, 9]. The analysis of the authors is based on linear acoustic theory. In the analysis, it is considered that the secondary acoustic resonator is coupled acoustically to a primary resonator, i.e. the HS tube through the medium. The coupling produces mutual acoustic inductance, and it results in the increase of total impedance at the entrance of the HS tube. The frequency hysteresis shown in Fig. 2 is clearly explained by the characteristics of the imaginary part of the coupling impedance, i.e. coupling reactance [7].

The real part of the impedance, i.e. coupling resistance, remarkably increases just before frequency jumps. The end wall temperature drops shown in Fig. 2 correspond to this. Temperature rise in the region of $L_S/L_T > 1$, however, cannot be explained by acoustic theory alone. To consider the change of the end wall temperature, variations of the operational mode of the HS tube coupling the secondary resonator are observed with shock structures appearing in jet flows and with pressure histories in the tube.

Shock structures in jet flows are shown in Fig. 3.1 by Schrielen photographs exposed for several periods of oscillation (about 20 ms). The symbols (a), (b), (c) and (d) in Fig. 3.1 correspond to those in Fig. 2. Shock oscillation in jet flow by repetitive phase changes of inflow and outflow at the entrance of the HS tube depends on operation mode of the tube. The changes of operation mode in the HS tube are explained by acoustic theory in some degree.

In the region of $L_S/L_T < 1$, the increment of reactance by the coupling assumes an aspect of inductance, i.e. additional mass, and it is a cause for imperfect reflections of waves propagating in the tube at its entrance. In this case, oscillation frequency decreases, and shock in the jet flow moves continuously according to gradual phase changes of inflow and outflow at the tube entrance. In the region of $L_S/L_T > 1$, the increment of reactance assumes an aspect of capacitance, and it tends to perfect reflections of waves at the tube entrance. In this case, frequency increases, and shock in the jet flow is displaced discontinuously owing to quick phase changes at the tube entrance.

Pressure histories in the tube at $X = 0.4$ are shown in Fig. 3.2. These are closely related with shock structures shown in Fig. 3.1. The quick phase change at the tube entrance brings rapid steepening of incident compression waves to shock wave as shown in case (c) or (d). Imperfect reflections of waves propagating in the tube at its entrance reduces shock strength.

These results show that an increase in mass or in coupling resistance by coupling of the secondary resonator supresses the thermal effect of the HS tube, however, proper additional acoustic capacitance improves it.

3. EFFECT OF A ROD LAID ALONG CONVERGENT NOZZLE AXIS

The HS tube is worked in the case when the tube mouth is placed in specific regions along centre axis of under-expanded jet flows issuing from a convergent nozzle [10]. The strength of oscillation in the tube depends on the nozzle pressure ratio (inlet/outlet pressures ratio) and on the spacing between the nozzle exit and the tube entrance.

When a convergent nozzle with thin rod laid along its axis is used, the HS tube is not only worked by subsonic jet flows but also the strength of oscillation in the tube is increased for supersonic operation of the HS tube.

In this section, effects of the use of the nozzle with rod on the thermal effect of the HS tube are observed.

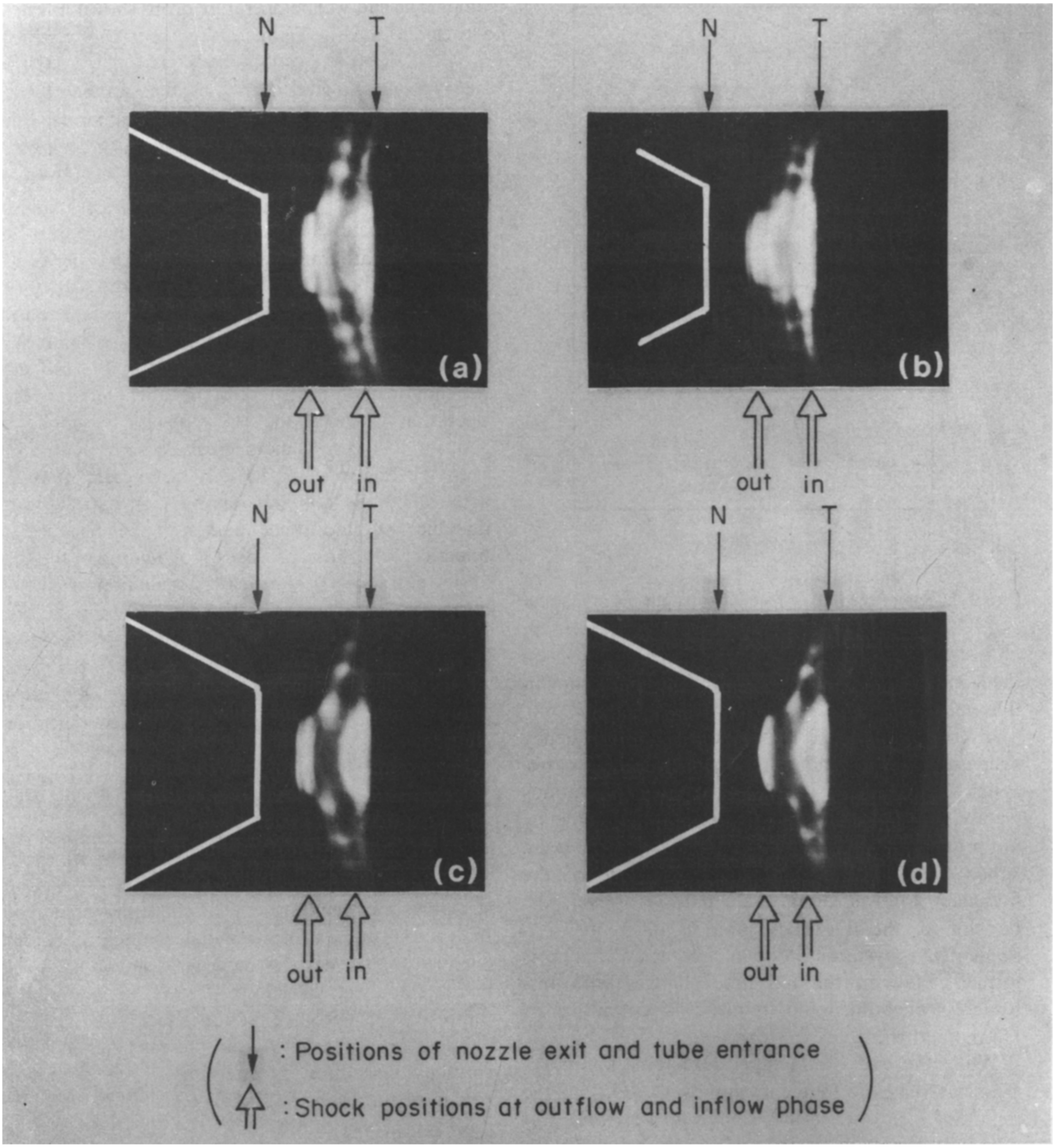

FIG. 3.1. Schrielen photographs of shock structures appearing in jet flows between nozzle exit and tube entrance.

The structures of under-expanded jet flows can be presented by total pressure curves measured along these axes. These curves usually present a periodic decrease and increase. When a thin cylindrical rod is laid along the central axis of the convergent nozzle, the periods of the total pressure curves of under-expanded jet flows are broken, and the total pressure curves of the subsonic jet flows present the same features as under-expanded jet flows.

Examples of total pressure curves of moderately under-expanded jet flows ($p_{IN}/p_{\infty} = 2.94$) issuing from both nozzles, i.e. with and without rod, are shown in Fig. 4, where the diameters of these nozzle exits and thin rods are 5 mm/1 mm respectively. The geometrical configurations of the measuring system of total pressure is shown in Fig. 4.

When the HS tube is worked by jet flow issuing from the nozzle without rod, the first working zone is in the region of $1.1 \sim l/D_N \sim 1.6$. Using the nozzle with rod, the HS tube is worked in the region $0.8 \sim l/D_N \sim 3.5$, and oscillation amplitude increases.

The effect of the use of the nozzle with the rod on wall temperature distribution of the HS tube is shown in Fig. 5. The wall temperature near the tube end rises

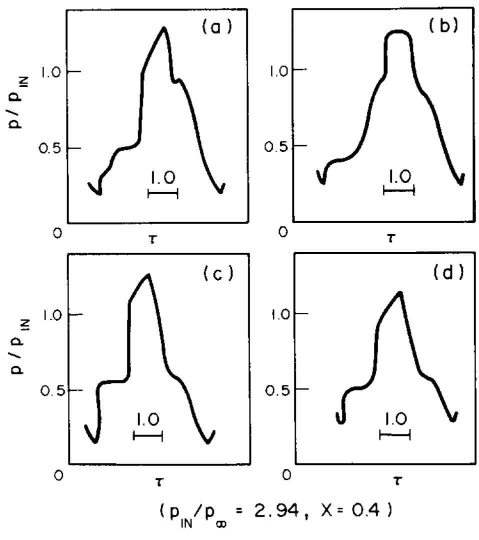

FIG. 3.2. Pressure histories in HS tube at $X = 0.4$.

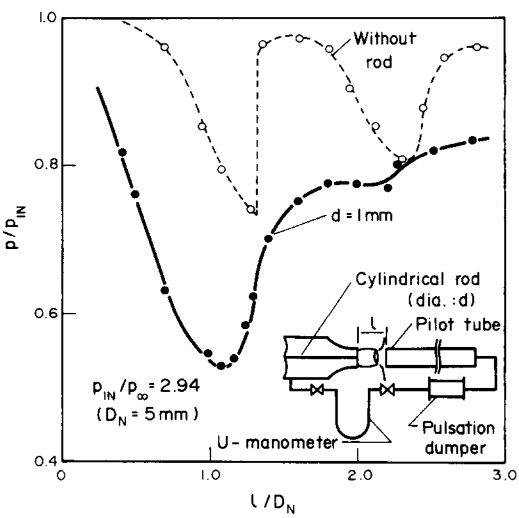

FIG. 4. Total pressure curves of under-expanded jet flows.

about 120 K by working with jet flow issuing from the nozzle with rod.

4. TEMPERATURE SEPARATION SYSTEM

4.1. *Apparatus*

Experimental apparatus of temperature separation by the HS tube coupling the secondary resonator is composed as shown in Fig. 6. The diameter of the nozzle exit is equal to the inner diameter of the HS tube ($D_N = D_T = 5$ mm). The thin rod diameter is 1 mm. The length of HS tube is 34 times of D_T considering Sprenger's experiment ($L_T = 170$ mm). The size of the hot-gas outlet bored at the end wall of the HS tube is varied in the region 0.6 ~ 2.6 mm ($0.014 \sim S_H/S_T \sim 0.27$). The length of secondary resonator is about

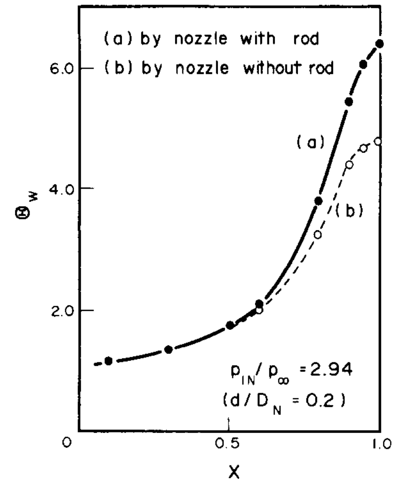

FIG. 5. Distributions of wall temperature of HS tube.

1.22 times of the length of HS tube ($L_S = 208$ mm).

The gas issuing from the nozzle and entering into the HS tube is separated into hot-gas and cold-gas. The former is discharged through the hot-gas outlet and is collected in the hot-gas chamber. The latter is discharged from the open end of secondary resonator. Stagnation temperature of hot gas in the hot-gas chamber and total temperature of flow in the secondary resonator (cold gas) are measured by chromel–alumel thermocouples. The fraction of hot gas is controlled by regulating a valve placed at the exit of hot-gas chamber. The capacity of the chamber is large enough to dampen pulsation for measurement of the fraction of hot-gas by an orifice flow meter.

The outside of the HS tube is insulated against heat by ceramic, the inside of the hot-gas chamber by calcium silicate and the outside by composite of glass wool and asbestos, respectively.

4.2. *Experimental results and considerations*

The effects of temperature separation are observed for supersonic and subsonic operations of the HS tube.

Experimental results for nozzle pressure ratios p_{IN}/p_∞ 2.94 and 3.91 are shown in Figs. 7.1 and 7.2, where the nozzle inlet temperature T_{IN} is 293 K. These figures show the effects of the hot-gas fraction on nondimensional temperatures of hot gas and cold gas and on pressure in the hot-gas chamber for different sizes of hot-gas outlet.

At zero fraction of hot gas, the temperature of the hot gas is very high. For pressure ratio $p_{IN}/p_\infty = 2.94$, the hot-gas temperature is raised up about 310 K to the nozzle inlet temperature (i.e. $T_H - T_{IN} \simeq 310$ K), and the cold-gas temperature is dropped about 6 K (i.e. $T_{IN} - T_C \simeq 6$ K). For pressure ratio $p_{IN}/p_\infty = 3.91$, $T_H - T_{IN} \simeq 380$ K and $T_{IN} - T_C \simeq 5$ K. As the hot-gas fraction increases, while the pressure in the hot-gas chamber decreases gradually, the hot-gas temperature rapidly goes down. The cold-gas temperature drops a

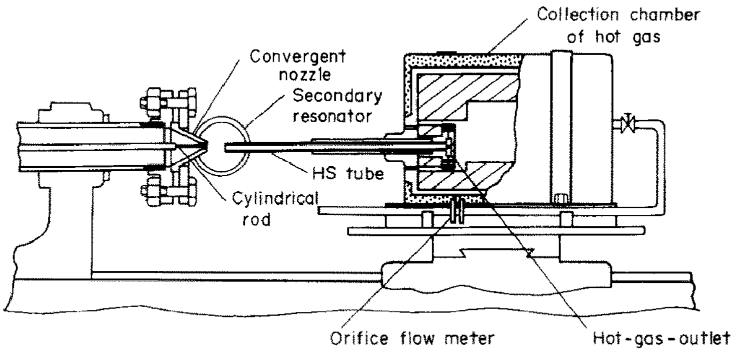

FIG. 6. Experimental apparatus of temperature separation.

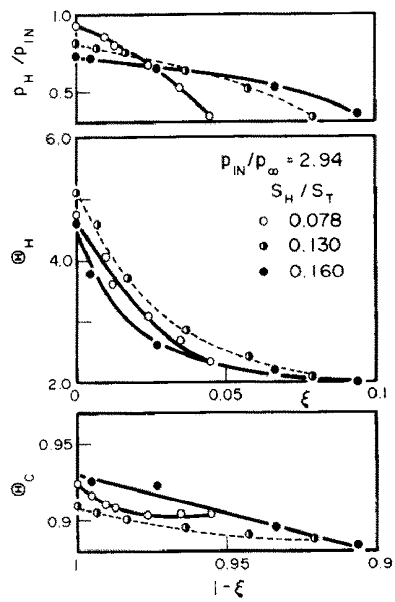

FIG. 7.1. Effects of hot-gas fraction on the temperatures of hot gas and cold gas and on pressure in the hot-gas chamber (for $p_{IN}/p_\infty = 2.94$).

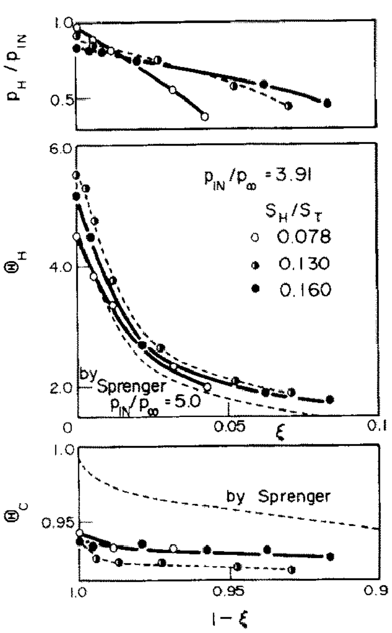

FIG. 7.2. Effects of hot-gas fraction on temperatures of hot gas and cold gas and on pressure in hot-gas chamber (for $p_{IN}/p_\infty = 3.91$).

few degrees as the fraction increases. The maximum fraction of hot gas depends on the size of hot-gas outlet, and changes of pressure in the hot-gas chamber and temperatures of hot gas and cold gas also partly depend upon it. Sprenger's experimental result for the case of operation by highly under-expanded jet flow ($p_{IN}/p_\infty = 5.0$) shows a similar tendency to results obtained in this investigation as shown in Fig. 7.2 (however the size of hot-gas outlet is not known).

Effects of the hot-gas fraction on the efficiency of temperature separation for different pressure ratios and for various sizes of hot-gas outlet are shown in Fig. 8, where the efficiency is defined by

$$\eta = \frac{T_C - T_{IN}}{\Delta T_{ad}}. \tag{2}$$

The efficiencies increase as the hot-gas fraction increases.

Experimental results for subsonic operations are shown in Fig. 9. At zero fraction of hot gas, $T_H - T_{IN} \simeq 51$ K and $T_{IN} - T_C \simeq 2$ K. In this case, the hot-gas fraction range is narrow, because subsonic operations of the HS tube with discharge at the tube end are unstable.

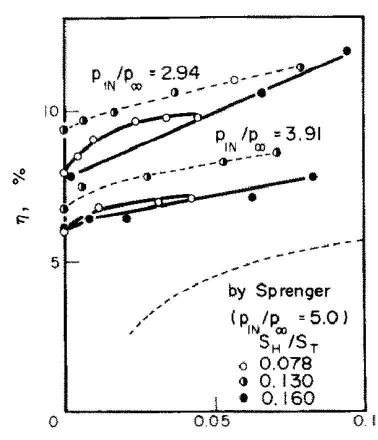

FIG. 8. Effects of hot-gas fraction on efficiency of temperature separation for different pressure ratios and for various sizes of hot-gas-outlet.

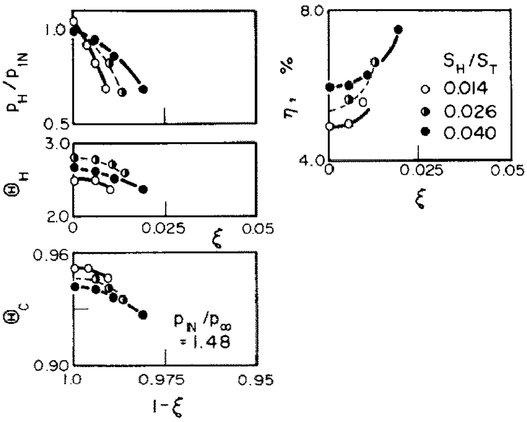

FIG. 9. Experimental results for subsonic operations.

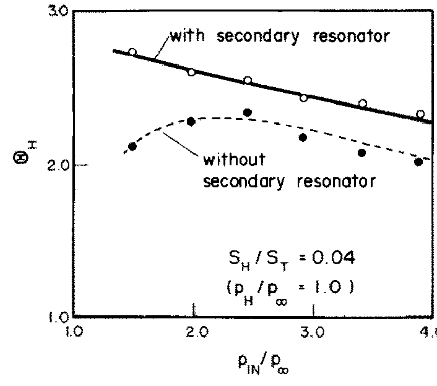

FIG. 12. Effects of pressure ratio and of coupling of secondary resonator on hot-gas temperature.

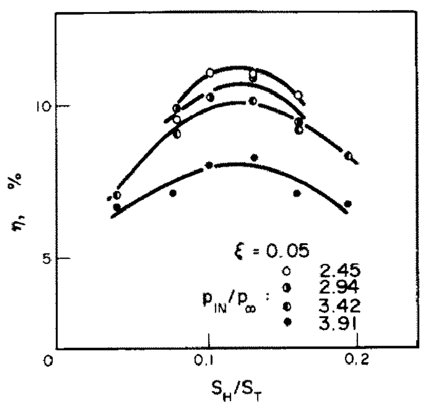

FIG. 10. Effects of hot-gas-outlet size on separation efficiency for different pressure ratios.

The effects of the size of the hot-gas outlet on the efficiency of temperature separation for various pressure ratios are shown in Fig. 10. This figure shows that there is optimum size of hot-gas outlet for the separation efficiency in the cases of supersonic operations, and it is $S_H/S_T \simeq 1.2$.

The effects of nozzle pressure ratio on the efficiency are shown in Fig. 11. When the apparatus for temperature separation is worked by moderately under-expanded jet flows, the efficiency is at its highest. It is interesting that Sprenger's result can be obtained by extrapolating the curve plotting the results obtained in this investigation as shown in Fig. 11. This suggests that the effect of coupling of the secondary resonator on the thermal effect is reduced when the HS tube is worked by highly under-expanded jet flows.

The effects of pressure ratio and of the coupling the secondary resonator on the hot-gas temperature are shown in Fig. 12. It is found that the coupling effect of the secondary resonator decreases as pressure ratio increases.

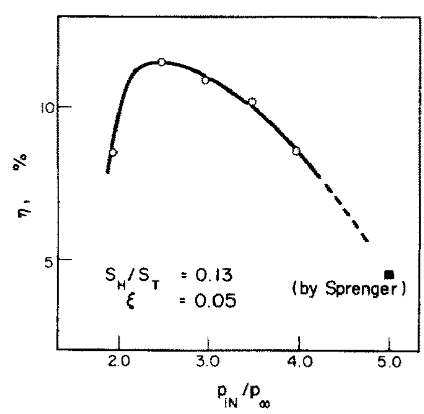

FIG. 11. Effects of pressure ratio on separation efficiency.

5. CONCLUSIONS

The conclusions of the present investigation are as follows: (1) Coupling of the secondary resonator to the HS tube or the use of the nozzle with the thin rod laid along its axis can improve the strength of oscillation in the HS tube and its thermal effect under proper geometric configuration. (2) The efficiency of the temperature separation in this investigation is highest in the case where the HS tube is worked by moderately under-expanded jet flows. (3) There is optimum size of hot-gas outlet for the separation efficiency. (4) The effect of the coupling of the secondary resonator decreases in the cases of operations by highly under-expanded jet flows.

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SEPARATION DE TEMPERATURE PRODUITE PAR UN TUBE HARTMANN–SPRENGER COUPLE A UN RESONATEUR SECONDAIRE

Résumé—Une séparation de température dans un gaz est produite par le tube Hartmann–Sprenger (HS) alimenté par un écoulement de jet sortant d'une tuyère convergente. La séparation de température dépend des effets thermiques du tube HS.

Le couplage d'un résonateur secondaire au tube HS ou l'utilisation d'une tuyère convergente avec une mince tige le long de son axe change le mode du tube HS et peut augmenter l'intensité de l'oscillation dans le tube et l'effet thermique.

Dans cette étude on considère les effets du résonateur secondaire et de l'utilisation de la tuyère avec la tige sur le comportement thermique. On réalise un montage pour la séparation de température et les caractéristiques de la séparation sont étudiées pour différents modes opératoires du tube HS et pour différentes tailles de la sortie du gaz chaud.

A partir des résultats expérimentaux, on trouve le mode opératoire optimal et la dimension optimale de la sortie pour le rendement de la séparation de température.

TEMPERATURTRENNUNG MIT DEM HARTMANN–SPRENGER-ROHR ANSCHLUSS EINES SEKUNDÄREN RESONATORS

Zusammenfassung—Temperaturtrennung eines Gases erfolgt im Hartmann–Sprenger (HS)-Rohr durch die Wirkung eines Freistrahls, der aus einer konvergenten Düse austritt. Die Temperaturtrennung hängt dabei von thermischen Effekten des HS-Rohres ab.

Der Anschluß eines sekundären Resonators an das HS-Rohr oder die Verwendung einer konvergenten Düse mit einem dünnen Stab in ihrer Achse ändert die Arbeitsweise des HS-Rohres, weil hierdurch die Stärke der Oszillationen und deren thermischer Effekt vergrößert werden können. In der vorliegenden Arbeit werden diese Einflüsse untersucht. Im Hinblick auf diese Effekte wurde ein Apparat zur Temperaturtrennung gebaut und seine Trennungscharakteristik für verschiedene Betriebszustände und unterschiedliche Größen der Auslaßöffnung für das heiße Gas untersucht. Aus den Versuchsergebnissen wurde der optimale Betriebszustand und die optimale Größe der Auslaßöffnung des heißen Gases ermittelt.

ТЕМПЕРАТУРНОЕ РАЗДЕЛЕНИЕ С ПОМОЩЬЮ ТРУБКИ ХАРТМАНА–СПРЕНГЕРА (ХС), СВЯЗАННОЙ С ВТОРИЧНЫМ РЕЗОНАТОРОМ

Аннотация — Температурное разделение газа осуществляется с помощью трубки Хартмана–Спренгера (ХС), созданной струйным потоком, вытекающим из конфузора. Эффект температурного разделения зависит от тепловых эффектов ХС труб.

Сочленение вторичного резонатора с трубкой ХС или конфузором с тонким стержнем, расположенным вдоль оси, изменяет режим работы трубки ХС и может повысить силу колебаний в трубке ХС и увеличить роль тепловых эффектов.

В данной работе рассматривается влияние вторичного резонатора и сопла со стержнем на тепловые эффекты трубы. С учётом этих эффектов создан аппарат для температурного разделения и изучаются характеристики разделения для разных рабочих режимов трубки ХС и разных размеров сопла горячего газа.

На основе экспериментальных данных определены оптимальный рабочий режим и оптимальный размер сопла горячего газа для эффективного температурного разделения.