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論文内容要旨

Densification of cryogenic fluids is expected as a method to improve the performance of a rocket transportation system. Liquid hydrogen and liquid oxygen are used as the propellants of Japanese H-IIA rockets, which are so-called cryogenic fluids. Cryogenic fluids have much low density, which makes the propellant tanks huge. The huge propellant tanks increase total launch weight of rocket and depress the performance of rocket transportation system. Therefore, densified rocket propellants will be used.

Thermophysical properties of cryogenic fluids have a strong dependence on the fluid temperature. Thus, cryogenic rocket propellants are easily densified by subcooling. Subcooling of cryogenic rocket propellants has several advantages such as an increase in liquid density and a reduction in saturated vapor pressure. An increase in liquid density reduces a volume of rocket propellant tanks as mentioned above. A reduction in saturated vapor pressure suppresses occurrence of cavitation in rocket engine turbo pumps, which enables to improve the performance of rocket engine turbo pumps.

However, densified cryogenic propellants also have several disadvantages. Cavitation can still occur in the densified cryogenic propellants, although it is rare. Once cavitation occurs, cavitation can grow dramatically in subcooled propellants because thermodynamic effect suppressing bubble growth becomes weak in subcooled cryogenic propellants. Dramatic growth of cavitation amplifies flow instabilities in flow machineries. In particular, choking at throats between blades of an inducer can occur with cavitation because speed of sound reduces as an increase in void fraction and a reduction in the fluid temperature. Choking by cavitation always occurs in water because speed of sound with void fraction is much lower at the throats than the flow velocity required for cavitation. However, choking by cavitation does not always occur in cryogenic fluid because speed of sound with void fraction closes to the flow velocity required for occurrence of cavitation at the throats. Consequently, flow

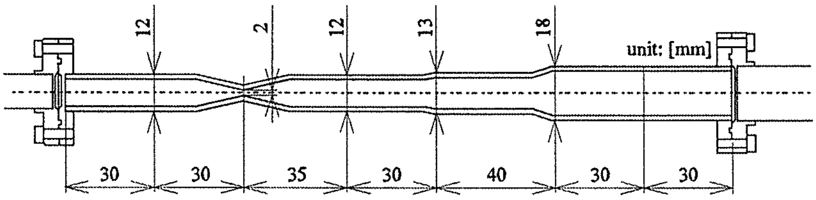

Fig. 1 Schematic diagram of a converging-diverging nozzle

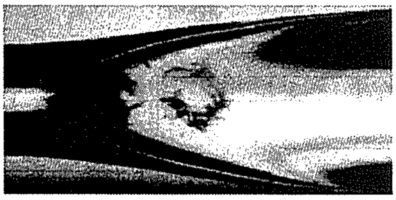

Fig.2 Picture of cavitation (Cavitation is shown as black shadow.)

instabilities are considered to be amplified by repeating choke and release at the throat.

Flow instabilities induced by choking in cavitating flows have not yet been clarified in subcooled cryogenic fluids. Therefore, experiments on cavitating flows at a converging-diverging nozzle with subcooled liquid nitrogen were carried out in order to clarify the characteristics of flow instabilities induced by cavitation choking flows in subcooled cryogenic fluids. In particular, attention was paid to the dependence of flow instabilities on the fluid temperature in the present study.

In experiments, visualizations of cavitating nozzle flows were carried out with a high-speed video camera. A converging-diverging nozzle used in the present study is shown as a schematic diagram in Fig. 1 and a visualized picture of cavitation is shown in Fig. 2. Moreover, pressure fluctuations upstream and downstream are measured by piezoelectric pressure sensor so that high-frequency pressure fluctuations can be captured in detail.

Cavitation characteristics in liquid nitrogen nozzle flows

In this chapter, flow instabilities occurred in cavitating nozzle flows with subcooled liquid nitrogen was elucidated by comparison between cavitation in normal liquid nitrogen at 77 K and that in subcooled liquid nitrogen at 69 K.

1. Cavitation can continue to occur stably in the normal condition at 77 K. The upstream static pressure of the visualization nozzle increases gradually when the flow begins and tends toward the first steady-state value as long as cavitation does not occur. Once cavitation occurs, the upstream static pressure of the nozzle increases gradually again and tends toward the second steady-state value during cavitation. Although a pulsed pressure fluctuation is observed with the occurrence of cavitation, the amplitude of this fluctuation is not so large.
2. Cavitation cannot continue to occur stably in the subcooled condition at 69 K. As in the case of the normal condition, the upstream static pressure of the visualization nozzle increases gradually when flow begins and tends toward the first steady-state value as long as cavitation does not occur. However, a dramatic pressure fluctuation occurs upon the occurrence of cavitation, and the cavitation behavior becomes pulsed and cannot be maintained stably. The upstream static pressure does not increase toward the second steady-state value, and only a pulsed pressure fluctuation is observed.

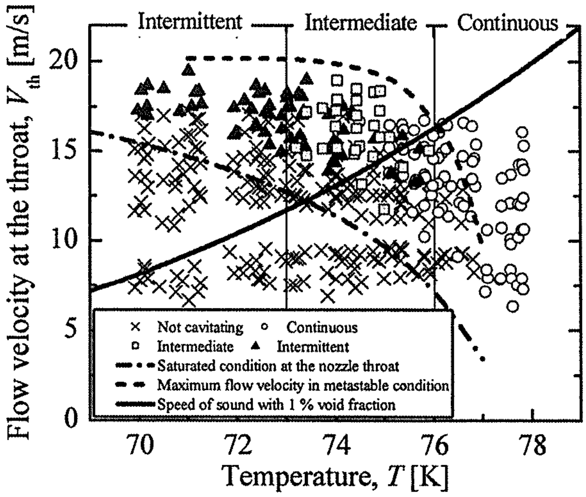

Fig. 3 Distribution of cavitation instabilities (Circle: continuous cavitation, Square: Intermediate cavitation, Triangle: Intermittent cavitation)

3. The instability of cavitation in the subcooled condition is considered to be caused by a reduction in the speed of sound in a gas-liquid two-phase flow with an increase in the void fraction and a reduction in the fluid temperature. A reduction in the speed of sound causes a choking flow at the nozzle throat, which results in an increase in the upstream static pressure. The increase in the upstream static pressure induces an oscillation in the piping system and the disappearance of bubble clouds. Consequently, cavitation cannot be maintained stably in the subcooled condition.

Cavitation instabilities in subcooled liquid nitrogen nozzle flows

In this chapter, the dependence of the flow instabilities on the fluid temperature was elucidated by experiments of cavitating nozzle flows at various fluid temperatures.

1. Cavitation behaviors can be classified to three types: continuous cavitation, intermediate cavitation, and intermittent cavitation. The distribution is shown in Fig. 3. Continuous cavitation occurs above 76 K. In case of continuous cavitation, the upstream static pressure increases gradually, and cavitation can continue to occur stably. Intermediate cavitation occurs between 73 K and 76 K. When cavitation occurs in this temperature range, cavitation appears and disappears repeatedly. A strong pulsed pressure fluctuation then occurs with the occurrence of cavitation, and the volumetric flow rate decreases dramatically. Intermittent cavitation occurs below 73 K. When cavitation occurs in this temperature range, cavitation cannot be maintained and so occurs intermittently. Furthermore, pulsed pressure fluctuation occurs with the occurrence of cavitation, although the amplitude is smaller than that of intermediate cavitation.
2. The first boundary of cavitation behaviors is considered to exist at 76 K in this experimental system and is considered to be an intersection between the estimated curve of the speed of sound with a 1% void fraction and the estimated curve of the required volumetric flow rate for the occurrence of cavitation. The second boundary of cavitation behaviors is considered to exist at 73 K in this experimental system and is considered to be an intersection between the estimated curve of the speed of sound with a 1% void

fraction and the estimated curve of the required volumetric flow rate for cavitation conservation.

3. The pressure fluctuation is divided to three regions based on frequency and is considered to correspond to cavitation behaviors. The low-frequency component of the pressure fluctuation indicates a pulsed behavior and corresponds to the occurrence of cavitation. The middle-frequency component of the pressure fluctuation indicates an oscillation of several hundred Hertz and corresponds to the oscillation of bubble clouds. The high-frequency component of the pressure fluctuation indicates an oscillation that has a frequency characteristic that is proportional to f^2 and corresponds to bubble collapse downstream of the nozzle.

Mechanisms and characteristics of subcooled cryogenic cavitation

In this chapter, the mechanism of flow instabilities caused by cavitation and the characteristics of pressure fluctuations induced by the flow instabilities are clarified.

1. Cavitation instability is considered to be caused mainly by a dramatic reduction in the speed of sound in a gas-liquid two-phase flow with an increase in the void fraction at the nozzle throat and a reduction in the fluid temperature. Continuous cavitation occurs above a temperature at which the estimated curve of the speed of sound with a certain void fraction intersects with the estimated curve of the required flow velocity for the occurrence of cavitation. Intermittent cavitation occurs below a temperature at which the estimated curve of the speed of sound with a certain void fraction intersects with the estimated curve of the required flow velocity for cavitation conservation. Intermediate cavitation occurs between the above-described temperatures.
2. The instability of the intermediate cavitation is considered to be caused by the wideness of the cavitation hysteresis, which is the difference between the required flow velocity for the occurrence of cavitation and the flow velocity at which cavitation disappears. When cavitation occurs at high flow velocity, which is required for the occurrence of cavitation in this temperature range, the flow velocity is depressed to the speed of sound with a certain void fraction and a strong pressure fluctuation occurs. Since the required flow velocity for cavitation conservation is lower than the speed of sound, cavitation can occur continuously. However, since the difference between the disappearing flow velocity and the speed of sound is small, cavitation may disappear.
3. The instability of the intermittent cavitation is considered to be caused by the narrowness of cavitation hysteresis. When cavitation occurs in this temperature range, the speed of sound decreases dramatically instantly to below the required flow velocity for cavitation conservation, and cavitation then disappears before the flow at the nozzle throat becomes completely choked. Therefore, the amplitude of the pressure fluctuation is small.
4. Low-frequency components of pressure fluctuations are caused by the water hammer phenomenon with the occurrence of cavitation. High-frequency components of pressure fluctuations are induced by fluctuations of the void fraction at the nozzle throat. These amplitudes are affected by the degree of superheat before cavitation occurs, and the assumption was validated by experiments in which cavitation easily occurs before the saturated condition by using liquid nitrogen with numerous bubble nuclei.

論文審査結果の要旨

次世代型宇宙往還機や超伝導送電システムの開発において，極低温流体機器の更なる高性能化，低コスト化が必要とされており，有力な候補として，大気圧沸点以下に冷却して低温化と高密度化を図ったサブクール極低温流体の実用化が検討されている。極低温流体は通常流体に比べ蒸発潜熱，表面張力，気液の密度比が小さいなど特異な物性を有するため，侵入熱，圧力低下により容易に気液二相流を形成する。サブクール極低温流体が推進剤もしくは冷却剤として実用化された例は少なく，キャビテーション現象についても殆ど研究が行われておらず，流体機器の高性能化と密接に関連するキャビテーション発生時の流動挙動を解明することは極めて重要である。

本論文は，サブクール液体窒素を使用してノズル絞り部でのキャビテーション発生実験を行い，発生機構および発生時の圧力振動など不安定流動現象が気液二相化に伴うサブクール流体の物性値変化と密接に関連していることを明らかにし，これらの研究成果をまとめたものであり，全編5章からなる。

第1章は序論であり，本研究の背景，目的および構成を述べている。

第2章では，大気圧飽和状態およびサブクール状態での液体窒素のキャビテーション発生挙動について実験および解析を行い，サブクール状態ではキャビテーションが連続して発生せず，発生と同時に通常の数倍程度の圧力（流量）振動を伴い，短時間で消失することを実験的に確認している。この不安定性は温度低下および気液二相化（ボイド率変化）に伴うサブクール液体窒素の急激な音速低下によるチョーク流れが原因であることを解析的に示している。これは流動条件によりサブクール状態のキャビテーションが飽和状態とは異なる挙動を示す新しい知見であり，キャビテーションの流体機器に及ぼす影響が非常に大きいことを示しており，工学上極めて重要な成果である。

第3章では，サブクール状態におけるキャビテーション不安定現象を解明するため，サブクール度をパラメータとして系統的な実験を行い，3種類のキャビテーション形態が存在することを確認し，サブクール度と発生時の音速から各々の形態が発生する条件を定量的に初めて明らかにしている。即ち，①連続発生領域（飽和状態と同じ現象），②間欠発生領域，③中間領域である。①と②は，発生時の流速と音速の大小によりキャビテーションが連続発生する場合と1秒程度の短時間で消失する場合である。中間領域では極低温流体中に気泡核が少ないため，キャビテーションが発生する流速以上においても準安定状態を保持し，キャビテーションが発生するとチョーク流れに戻る際に大きな減速作用が働き，大きな圧力（流量）振動が発生する。これは，サブクール液体窒素のみでなく同様な流動条件となる極低温流体にも適用できる成果であり，工学上の設計指針として重要な成果である。

第4章では，中間領域で発生するキャビテーション不安定現象について，第3章で明らかにした現象確認のため，実験および圧力振動に関する解析を行っている。キャビテーション発生時の大きな低周波圧力振動は急激な流量低下に起因するものと考え，圧力振幅の推定法を提案し，定性的に一致することを確認している。また，絞り部で発生するクラウドキャビティ（気泡群の塊）の周期的変動が，付随して発生する高周波圧力振動の原因であることも示している。準安定状態の存在を確認するため，サブクール液体窒素中に気泡核が多い状態を再現して実験を行った結果，大きな圧力振動は発生せず，準安定状態への移行が中間領域での不安定要因の一つであることを明らかにしている。これは，サブクール極低温流体のキャビテーション不安定流動現象を説明する有用な知見である。

第5章は結論である。

以上要するに本論文は，サブクール液体窒素で発生するキャビテーション不安定現象について，広範な実験と解析により発生メカニズムおよび流動現象を明らかにしたばかりでなく，極低温機器の性能向上および致命的な損傷を防止する設計指針に貢献するものであり，航空宇宙工学および低温工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。