	きくた　けんご
氏　　　　　名	菊田研吾
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指　導　教　員	東北大学教授　升谷　五郎
論文審査委員	主査 東北大学教授　升谷　五郎　東北大学教授 大平　勝秀 東北大学客員教授 吉田　義樹　東北大学教授 井小萩　利明 東北大学教授　祖山　均

論文内容要旨

A rocket system characterized by large thrust and high performance uses cryogenic fluids as its propellant. To realize high combustion efficiency, it is necessary to supply the propellant at a high flow rate and high pressure to the combustion chamber. Therefore, a turbopump is installed in the rocket engine. Furthermore, at the inlet of the turbopump, the employment of inducers is necessary to meet the suction head requirement for the main impeller. However, due to low inlet pressure of the turbopmp, these inducers are used in cavitating condition.

Basically, cavitation is unstable, and many serious problems caused by cavitation occur in fluid machinery, such as noise, erosion, performance decrement, and instability. Furthermore, liquid rocket propellants are cryogenic fluids, such as liquid hydrogen and liquid oxygen, and cryogenic fluids generally have a large thermodynamic effect, which suppresses cavity growth. This thermodynamic effect influences the suction performance and the cavitation instabilities of the rocket turbopump. This thermodynamic effect also results in a decrease of the derived force, which is the difference between the ambient pressure and the saturated vapor pressure, for the cavity growth. This phenomenon is caused by the temperature depression due to vaporization, which removes evaporative latent heat from the ambient liquid. Although water is often used as the fluid in cavitation research, the characteristics of cryogenic fluids are considered to be quite different from those of water. Studies on the thermodynamic effect of cavitation have been done since the 1950's, but the influence of the thermodynamic effect on the performance of pumps and the degree of the thermodynamic effect in cryogenic fluid have not yet been clarified. One of the reasons for the lack of understanding of these factors is the difficulty of observing the cavitation in rotating blades. In particular, the difficulty increases when cryogenic fluids are used as the working fluids of the pump.

However, it is necessary to observe the developmental state of cavitation in a cryogenic inducer to improve our understanding of the thermodynamic effect because the thermodynamic effect is caused by cavitation. Therefore, the purpose of the present study was to clarify the characteristics of the thermodynamic effect in cryogenic fluid, and furthermore, to clarify the influence of the thermodynamic effect on the cavitation performance and the onset of cavitation instabilities of the inducer of the rocket turbopump. For this purpose, two types of experiments were conducted, namely, those in which the thermodynamic effect can be disregarded and those in which it distinctly appears.

To observe cavitation phenomena occurring in a cryogenic inducer in more detail, inducer experiments in liquid nitrogen, as experiments in which the thermodynamic effect distinctly appears, were conducted at the Cryogenic Inducer Test Facility (CITF), conducted by the Japan Aerospace Exploration Agency (JAXA) at the Kakuda Space Propulsion Center. Some equipment and sensors in the facility have special specifications because of the cryogenic environment. The temperature of liquid nitrogen can be changed from 73 K to 86 K in this facility, and the experiments in which thermal properties are changed can be conducted by using this function. Furthermore, to determine the developmental state of cavitation, fluctuating pressure sensors are installed on the casing because direct optical visualization cannot be done in liquid nitrogen. As direct optical visualization could not be done in liquid nitrogen, unsteady pressure sensors were installed on the casing to estimate the cavitation region. This region can be estimated by using the fluctuating pressure sensors. Here, cavity length of the tip cavitation was adopted as an indication of cavitation.

Examination of the relation of cavity length to cavitation performance and the onset of cavitation instabilities (i.e., sub-synchronous rotating cavitation and cavitation surge) was conducted by comparison of results in liquid nitrogen set at different temperatures, 76 K and 80 K, with those in cold water at 296 K. From the experimental results, the temperature depression ΔT can be estimated from the difference of the cavitation numbers, σ_c- σ, of two corresponding conditions. The value σ_c is obtained from the experimental result without the thermodynamic effect (i.e., in cold water), while the value σ is obtained from the experimental result with the thermodynamic effect (i.e., in liquid nitrogen). The estimated temperature depression ΔT was found to increase with an increase of the cavity length, particularly when the cavity length extended over the throat of the blade passage, and that indicated a limit in the case of 76 K. From these results, it was found that the thermodynamic effect depends on the cavity length and that the temperature depression is limited when the temperature in the cavity nearly reaches the temperature of the triple point of liquid nitrogen. It was inferred that the small margin between the temperature and that of the triple point of the cryogenic fluid, e.g., liquid nitrogen, results in a limitation of the degree of the thermodynamic effect.

In addition, cavitation instabilities occurred both in liquid nitrogen and in cold water when the cavity length increased. Sub-synchronous rotating cavitation appeared both in liquid nitrogen and in cold water. In the experiment using liquid nitrogen, the temperature difference between 76 K and 80 K affected the range in which the sub-synchronous rotating cavitation occurred. It was concluded that sub-synchronous rotating cavitation is one type of the cavitation instability, mainly depending on the cavity length. On the other hand, deep cavitation surge appeared only in cold water at lower cavitation numbers. Cavitation surge is a kind of system instability which depends on the pump gain and unsteady characteristics of cavitation, i.e., mass flow gain factor and cavitation compliance. In the present experiment, it was inferred that the thermodynamic effect decreased the mass flow gain factor in liquid nitrogen and suppressed deep cavitation surge at lower cavitation numbers. From these experimental results, it was concluded that when the cavity length extends over the throat, the thermodynamic effect also affects the cavitation instabilities as a "thermal damping" through the unsteady cavitation characteristics.

Furthermore, the influence the thermodynamic effect on the blade load was investigated. Distribution of the blade load is important information as one of the design parameters for a cavitating inducer. The distribution of blade load gradually changes when cavitation occurs and develops in inducers. On the other hand, the thermodynamic effect on cavitation is significant in cryogenic fluid. Thus, the cavitation changes the distribution of the blade load and also causes the thermodynamic effect in cryogenic fluid. Therefore, to clarify this relationship, experiments in both cold water and liquid nitrogen were conducted with a focus on the development of cavity length.

In these experiments, the pressure rise along the blade tip was measured. In water, the pressure increased almost linearly from the leading edge to the trailing edge at higher cavitation number. After that, with a decrease of cavitation number, pressure rise occurred only near the trailing edge. On the other hand, in liquid nitrogen, the pressure distribution was similar to that in water at a higher cavitation number, even if the cavitation number as a cavitation parameter decreased. As the experimental result, the distribution of the blade load does not change even at lower cavitation number in the experiment in liquid nitrogen because the cavitation growth is suppressed by the thermodynamic effect. By contrast, the pressure distribution in liquid nitrogen has the same tendency as that in water if the cavity length at the blade tip is taken as an indication of cavitation. From these results, it was found that the shift of the blade load to the trailing edge depended on the increase of cavity length and that the distribution of blade load was indicated only by the cavity length independent of the thermodynamic effect. It was also found that "the same extent (length) of cavitation results in the same blade load distribution and results in the same damage to the performance in any working fluid." This is the "converse" of Stepanoff's assumption that "the same value of volume ratio V_V/V_L would mean the same extent of cavitation condition and the same damage to the performance", and it was confirmed in present study.

To estimate the influence of rotational speed (= velocity) on the thermodynamic effect, experiments in which the inducer rotational speed was changed in liquid nitrogen were then conducted. The temperature of liquid nitrogen was 79 K, and the rotational speed was set at 18300 rpm, 14000 rpm, and 10000 rpm. Furthermore, an experiment in which the fluid temperature was changed was also conducted. From comparison of these results, the difference between the influence of the transit time and that of the fluid properties on the thermodynamic effect was investigated. The temperature of liquid nitrogen was 86 K, and the rotational speed was 18300 rpm. As the experimental result, in the experiment with lower rotational speed, suction performance was improved. Comparison of results of the experiments in liquid nitrogen at the same cavitation number showed that the cavity length was suppressed at lower rotational speed. Thus, it was confirmed that the degree of the thermodynamic effect depends on the rotational speed as lower rotational speed suppresses cavity length. In addition, it was found that the degree of temperature depression became smaller when the rotational speed was lower.

The thermodynamic effect as estimated from the shift of cavitation number $\Delta\sigma$ cannot be expressed entirely by the non-dimensional thermodynamic parameter Σ^*, which consists of thermal properties of the fluid and dynamic fluid parameter, which are related to the velocity. Then, considering the condition at the temperature decreasing process, the modified non-dimensional thermodynamic parameter Σ^*_{mod} was suggested. It can indicate the relation with the shift of cavitation number $\Delta\sigma$, better than Σ^*. Thus, the effect of nonlinearity of the vapor pressure curve should be considered to evaluate the thermodynamic effect, especially in the case of a large increase of the temperature depression ΔT.

In addition, the influence of the temperature decreasing process on the thermodynamic effect was examined using a two-dimensional cascade model proposed by Watanabe et. al. In this analysis, instead of the Clapeyron equation, the actual (non-linear) P_v-T curve is applied corresponding to the temperature depression due to the thermodynamic effect. The shift of the cavitation number $\Delta\sigma$ due to the thermodynamic effect becomes smaller in the higher fluid temperature, even if that has the same Σ^*. This analysis result gives a good explanation of the present experimental result. When the thermodynamic effect occurs with large temperature depression, rather than considering the gradient of the linearized vapor pressure curve at the temperature of the infinity reference point, the physical properties changing with temperature depression in the process of cavity growth should be considered.

Furthermore, the shift of cavitation number $\Delta\sigma$ due to the thermodynamic effect in the present experimental results was examined with the convective heat transfer model, which evaluated the degree of the thermodynamic effect based on the comparison between the transit time τ and the thermal time required for the phase change τ_T. It was found that the shift of cavitation number $\Delta\sigma$ assumes a good correction by non-dimensional thermodynamic parameter τ/τ_T. The degree of influence of rotational speed U depends on how the Nusselt number Nu is defined in the model. Thus, more investigation is needed to apply the equation to define Nusselt number Nu.

Through the present study, a fundamental understanding of the thermodynamic effect was attained based on the cavity length of the tip cavitation. The characteristic of the thermodynamic effect in cryogenic fluid and the influence of thermodynamic effect on the cavitation performance and on the onset of cavitation instabilities were clarified. These findings are quite important information that should be considered when deciding the operational conditions and designing a new inducer. Therefore, these findings are useful for the progress not only in the development of a rocket turbopomp but also in physical research on the thermodynamic effect.

論文審査結果の要旨

ロケットエンジン用のターボポンプには，キャビテーションによる性能劣化を防ぐ目的で初段にインデューサが設置されるが，インデューサには激しいキャビテーションが発生する。一方，キャビティ気泡成長のためには気化熱の熱移動が必要であり，そのために気泡内の温度が降下し飽和蒸気圧は低下する。ロケットの推進剤である液体水素や液体酸素では，この温度降下が顕著であるため熱力学的な要素がキャビテーションの成長を抑制する効果を生む。従って，ロケット用インデューサでは熱力学的効果を定量的に把握し，これを設計に反映させることが重要な課題となっている。本研究では，極低温流体中でインデューサに発生するキャビテーション長さを測定する新しい計測法を構築し，計測データを元に熱力学的効果が吸込性能や非定常キャビテーションに与える影響を調べ，熱力学的効果を定量的に評価する無次元パラメータを提案している。本論文は，これらの研究成果をまとめたものであり，全編7章からなる。

第1章は序論であり，本研究の背景，課題，目的を述べている。

第2章では，極低温インデューサの実験装置の構成と機能，および新しく構築したキャビテーション長さの計測方法について述べている。計測装置の機能と精度，およびデータ処理方法を明確にし，その有効性を示している。

第3章では，流体の物性値がキャビテーションの熱力学的効果に与える影響を調べることを目的とし，液体窒素の温度を変化させた実験を行い，熱力学的効果が無視できる水試験でのキャビテーション長さとの比較から，熱力学的効果による温度降下量を推定している。その結果，流体の温度が降下し三重点に近づくと熱力学的効果の程度は漸減することを明らかにし，また熱力学的効果が非定常キャビテーションの振動を抑制することを明らかにしている。これらは極低温流体に発生するキャビテーションの熱力学的効果を定量的に示す重要な成果である。

第4章では，熱力学的効果がインデューサの翼負荷分布におよぼす影響を調べることを目的とし，水による実験と液体窒素による比較実験を行っている。この実験結果により，キャビテーション数が異なってもインデューサ翼端部のキャビテーションの長さをキャビテーション指標として考えた場合には，熱力学的効果に関わらずインデューサの翼負分布は同一となることを明らかにしている。これはインデューサの吸込み性能を向上させる翼負荷設計を考える上で有益な成果である。

第5章では時間の影響がキャビテーションの熱力学的効果に与える影響を調べることを目的とし，インデューサの回転数を変化させた実験を行っている。その結果，回転数が低いほどキャビティ気泡に熱伝導する時間が長くなり，気泡内の温度がより降下するためキャビティ気泡の成長が遅れ，その結果インデューサの揚程低下開始点は低キャビテーション数側にシフトすることを明らかにしている。これはターボポンプの運用状況の違いによる熱力学的効果の影響を評価する上で重要な成果である。

第6章では，熱力学的効果の程度を示す指標として，水の場合のキャビテーション数を基準としたキャビテーション数の改善効果量$\Delta\sigma$を選び，第 5 章までに得られた実験結果を元にして流体の物性と時間の影響を統一的に表す熱力学的無次元パラメータについて考察している。その結果，相変化の特性時間（τ_T ）とキャビティの発生から崩壊までに要する代表時間（τ）の比となる熱力学的無次元パラメータ τ/τ_Tが提案され，τ/τ_Tと$\Delta\sigma$の間には良い相関関係があることを示している。これは，極低温流体中のインデューサに発生するキャビテーションの熱力学的効果の予測法に貢献する重要な成果である。

第7章は結論である。

以上要するに，本論文はキャビテーションの熱力学的効果がインデューサの作動状況に与える影響を明らかにすると共に，極低温インデューサに発生するキャビテーションの熱力学的効果を定量的に評価するための熱力学的無次元パラメータを提示したものであり，航空宇宙工学及び流体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。