No. 1

TOKYO TECH Pursuing Excellence

インデューサーに発生する液体窒素・水キャビテーションの可視化

東京工業大学
伊藤 優

No. 2

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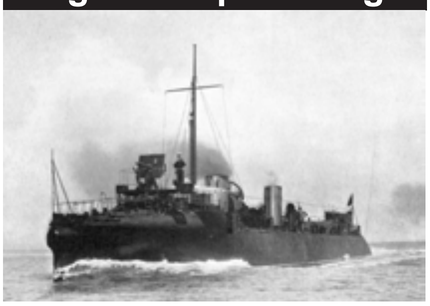
Background

Water Cavitation

In1894
English ship "Daring"



The performance of English ship "Daring" dropped unexpectedly due to water cavitation

→Research in water cavitation started especially in ship engineering field.

Cryogenic Cavitation

In 1999
Broken inducer of H-II rocket

The accident of H-II rocket was caused by unsteady LH_2 cavitation

→The clarification of behavior of cryogenic cavitation has been demanded.

Cavitation prediction method available for pump design is strongly desired associated with CFD simulation, recently.

Manned Transportation into Space

No. 3

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Soyuz-FG, Russia

Saturn V, USA

HII-B, Japan (freight only)

Launch rocket without solid rocket boosters is ideal for manned mission.
To do this, reliable liquid rocket engines with sufficient thrust are required !!

Cavitation Performance Curve

No. 4

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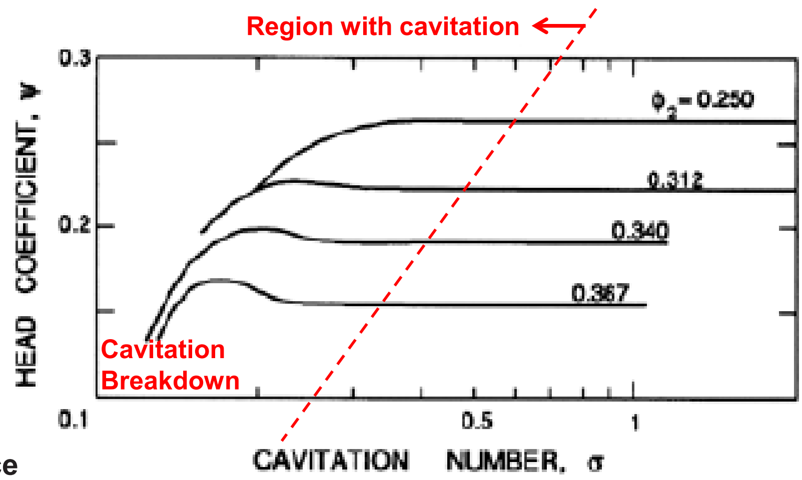
When **Cavitation Number** (which is a non-dimensional number for Net Positive Suction Head, or NPSH) approaches 0, **Cavitation Breakdown** occurs. It means that **Head Coefficient** (which is a non-dimensional number for Pump Head) is 0.
Just before Cavitation Breakdown,
there is a region in which **Maximum Head** is obtained.

Inducer of Turbo-pump
One of the most important components to decide performance in a liquid rocket engine

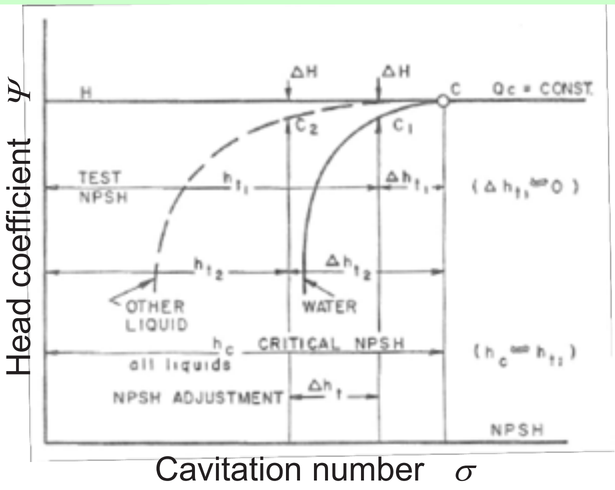


Establishment of a Design Method for Cryogenic Inducer Allowing Cavitation

What is Thermodynamic Effect ??

No. 5

Cavitation absorbs latent heat from ambient liquid as it grows.
Then, the ambient liquid temperature decreases.
As a result, cavitation growth is suppressed.
This phenomenon is called "thermodynamic effect".



Therefore, it is well known that
fluid with greater thermodynamic effect is less subject to cavitation breakdown.

What is Thermodynamic Effect ??

No. 6

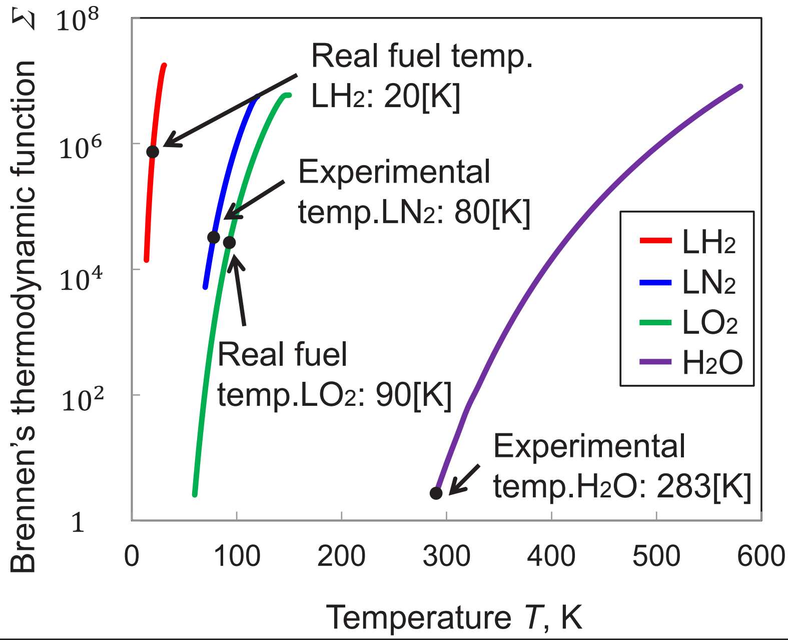
Cryogenic fluids have greater thermodynamic effect than cold water.
→Cryogenic pump is too high safety margin by using design method for water.
→More efficient cryogenic pump may be available by using specific design method to cryogen.

Thermodynamic Function

This parameter shows the magnitude of thermodynamic effect. It depends on a variety of fluid and fluid temperature.

$$\Sigma(T_\infty) = \frac{\rho_V^2 L_{LV}^2}{\rho_L^2 c_{PL} T_{\infty L} \alpha_L^{\frac{1}{2}}} [m/s^{\frac{3}{2}}]$$

ρ_V:vapor density
ρ_L:liquid density
$T_{\infty L}$:liquid ambient temperature
L_{LV}:laten heat
c_{PL}:liquid specific heat
α_L:liquid thermal diffisivity



Previous Studies

No. 7

In order to understand cryogenic cavitation in a rotating inducer,
its visualization is the best.
However there have been just two examples of visualization of cryogenic rotating inducer due to experimental difficulties.

NASA test facility

It was conducted by liquid hydrogen.

It can be only for liquid nitrogen.

JAXA test facility

The both can not conduct to visualize water cavitation in a rotating inducer and can not compare cryogenic cavitation with water cavitation.

Target of Present Study

No. 8

NASA test facility

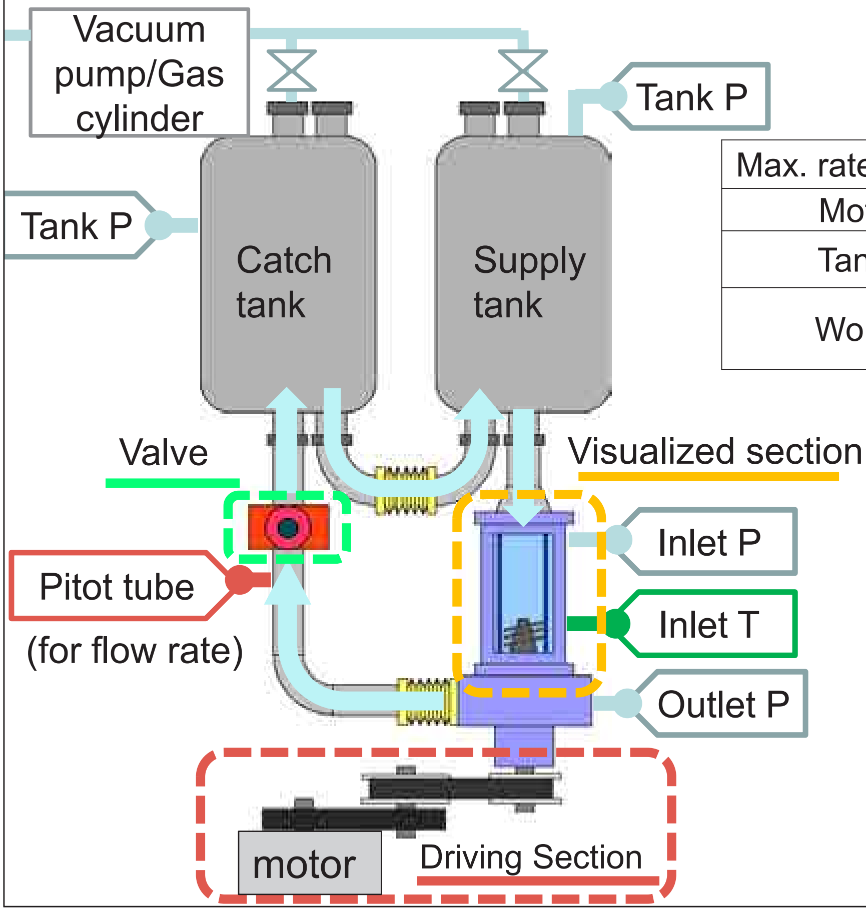
Target of Present Study

JAXA test facility

1: Visualize a rotating inducer in liquid nitrogen.
2: Visualize a rotating inducer in water in the same flow geometry. To do this, Keep the tip clearance between the inducer tip & the shroud casing at either of liquid nitrogen temperature & water temperature.
3: Compare cryogenic cavitation results with not only water cavitation results we conducted but also water cavitation results the others conducted.
4: Clarify the thermodynamic effect for a rotating inducer.
5: Feed knowledge back to a efficient cryogenic inducer.

Schematic View of Test Facility

No. 9



Basic specification

Max. rate of the inducer	6000rpm
Motor power	3.7kW
Tank volume	600L ×2
Working fluid	Liquid nitrogen Water

Inducer =Real LE-5 size

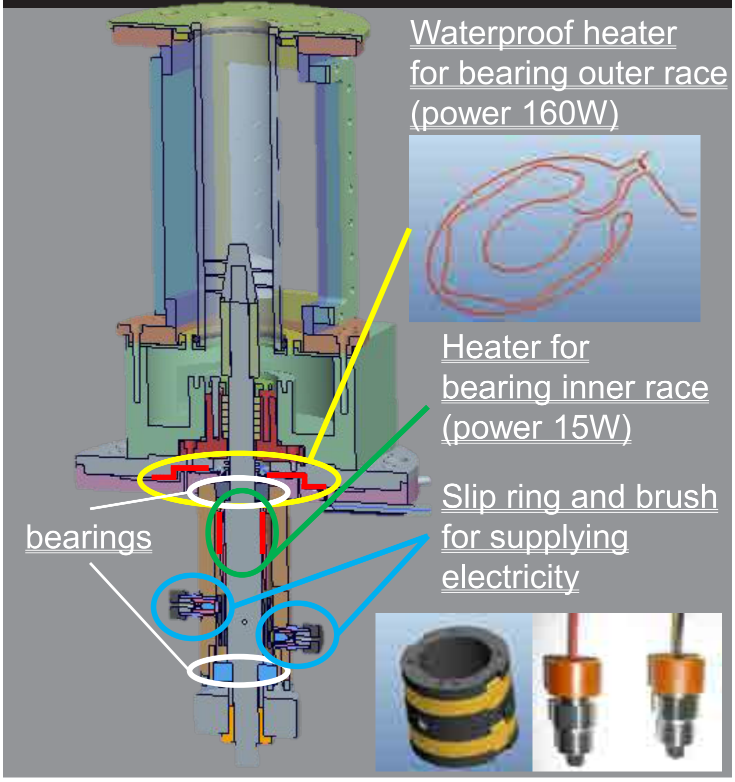
Tip diameter	65.3mm
Number of blade	3
Hub length	52mm
Inlet blade Angle	10°

Test Section for either LN_2 or Water

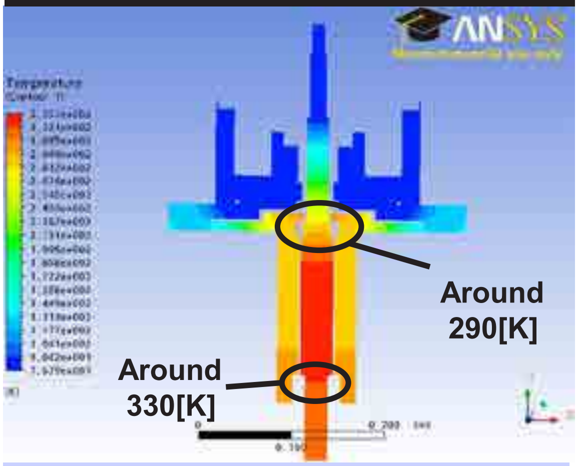
No. 10

LN2 experiment was failed by ice generation inside bearing.

Section of new test facility



Simulation result of temperature profile

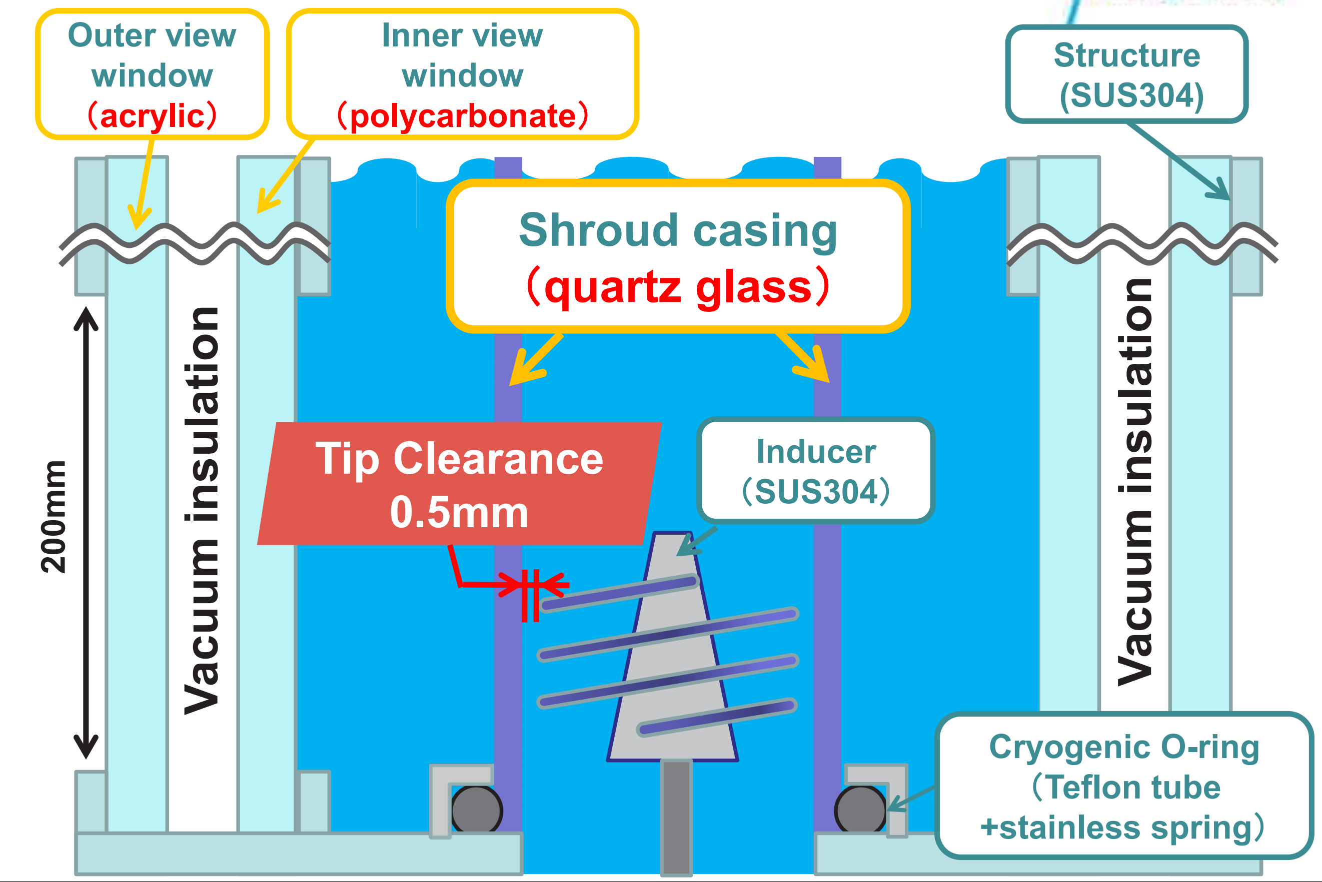


Boundary Condition

- Surfaces in contact with LN2:76K (isothermal wall)
- Surfaces in contact with atmosphere: T_{atom} =300 & Heat transfer coefficient h=20 [W/m^{2}K]

Schematic View of Test Section

No. 11

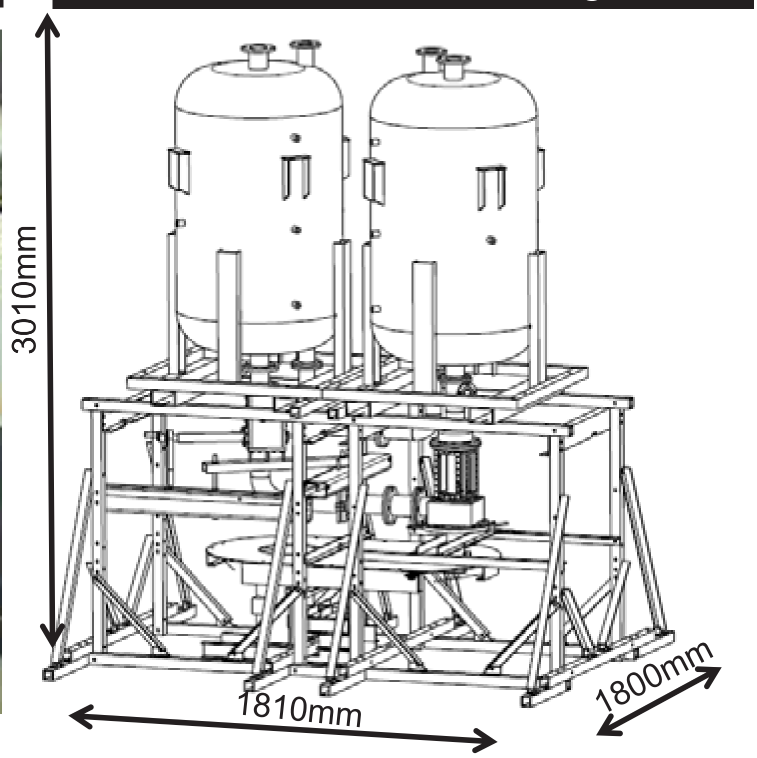


Overview of Test Facility

No. 12

Photo of test facility

Framework drawing



No. 13

Cavitation Development with Decrease of Cavitation Number σ

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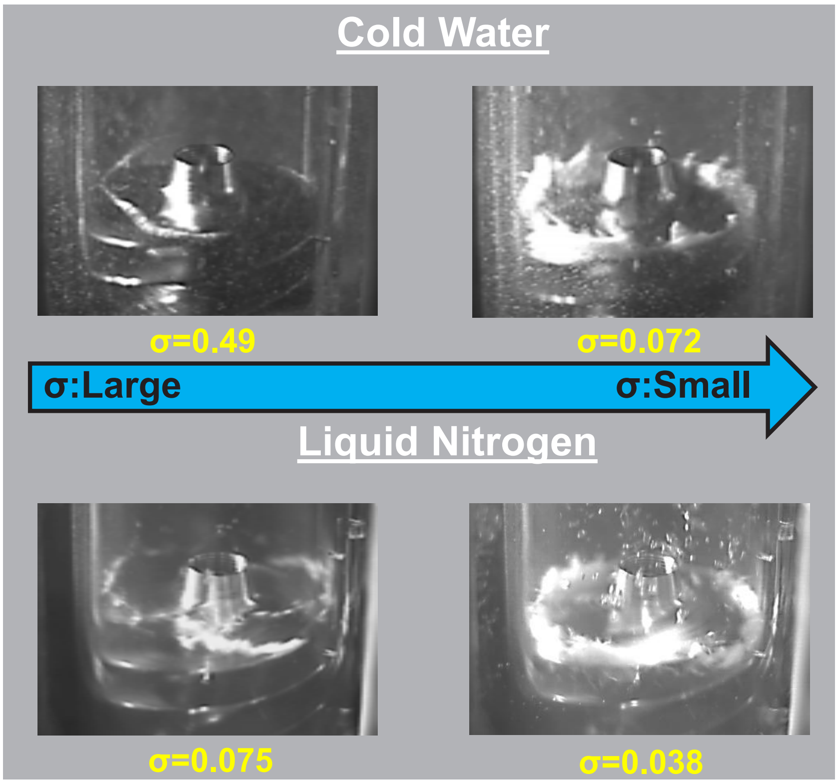

Flow coefficient ϕ =0.1

A variety of Cavitation

Tip vortex cavitation: occurs from the leading edge on the tip.

Backflow cavitation: occurs along the blade tip.

No. 14

Cavitation Development with Decrease of Cavitation Number σ

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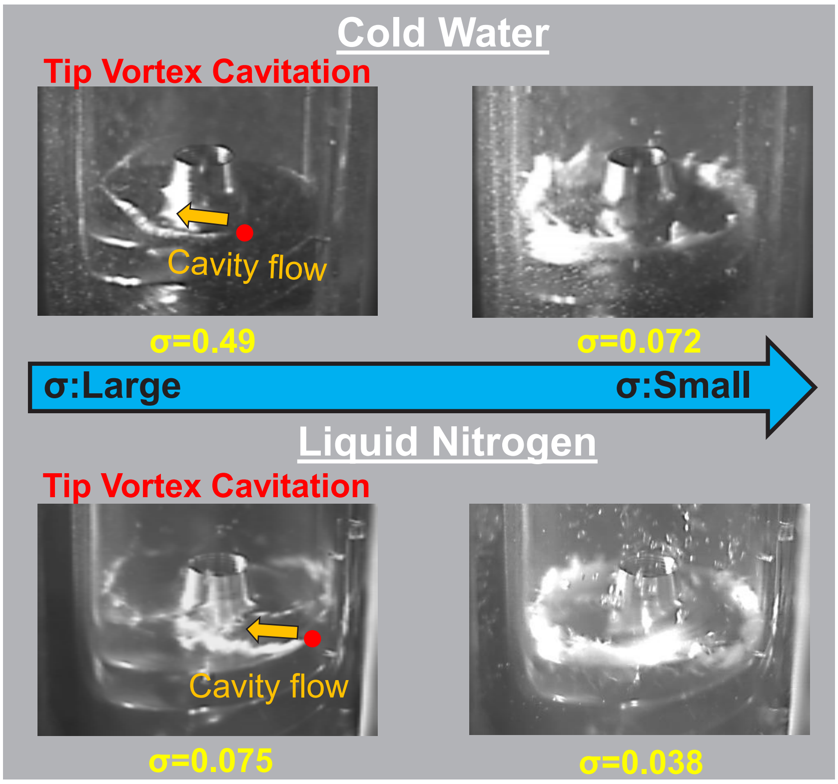


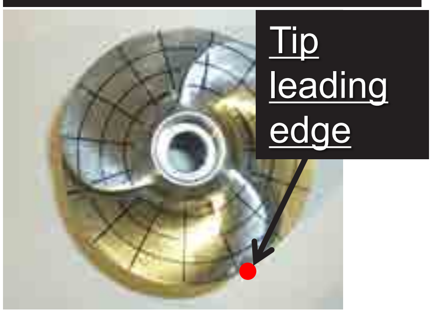
Flow coefficient ϕ =0.1

A variety of Cavitation

Tip vortex cavitation: occurs from the leading edge on the tip.

Backflow cavitation: occurs along the blade tip.

Tip Vortex Cavitation



No. 15

Cavitation Development with Decrease of Cavitation Number σ

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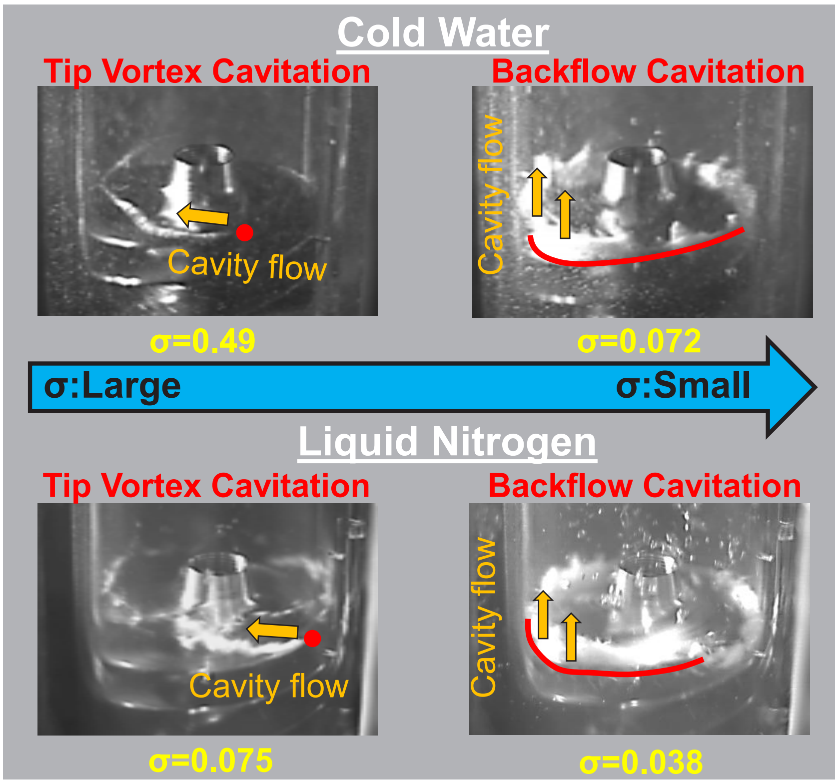

Flow coefficient ϕ=0.1

A variety of Cavitation

Tip vortex cavitation: occurs from the leading edge on the tip.
Backflow cavitation: occurs along the blade tip.

Backflow Cavitation

No. 16

Cavitation Development with Decrease of Cavitation Number σ

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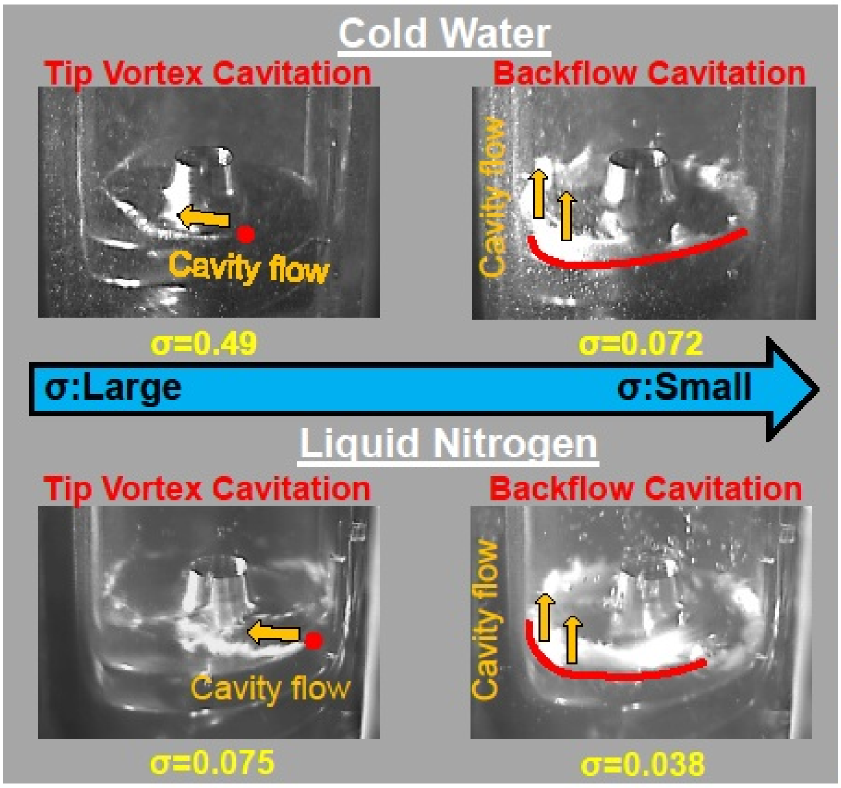

Flow coefficient ϕ=0.1

A variety of Cavitation

Tip vortex cavitation: occurs from the leading edge on the tip.
Backflow cavitation: occurs along the blade tip.

In both fluids, cavitation develops from tip vortex cavitation through backflow cavitation to breakdown. The same trend is observed at any ϕ.

Tip Vortex Cavitation

No. 17

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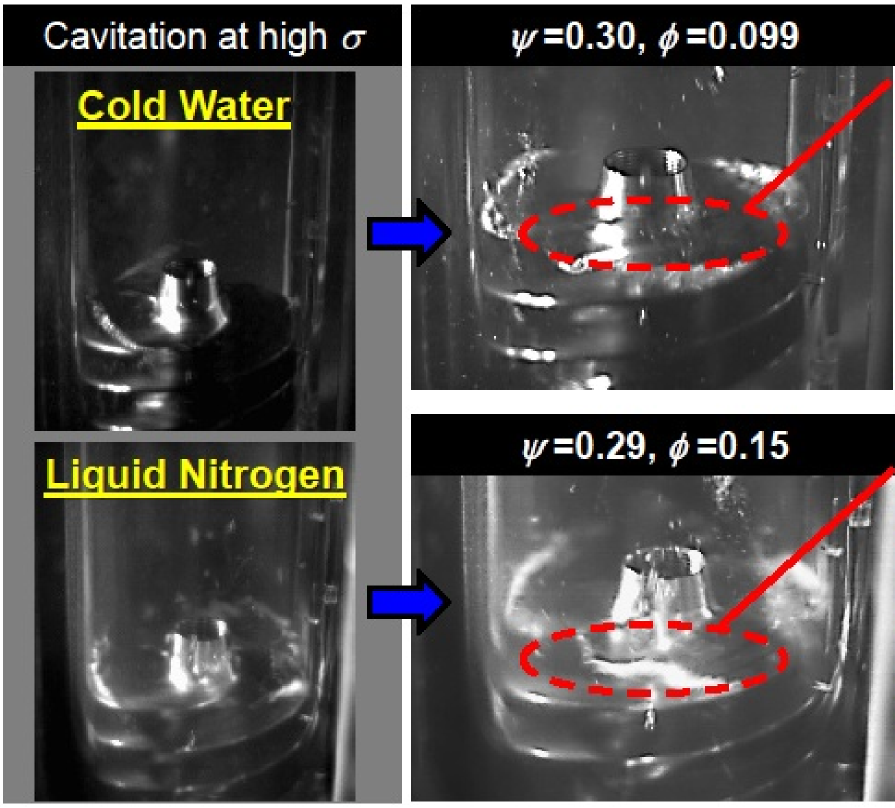
At any σ, ϕ and a variety of cavitation, the same brightness difference was observed.



Cavitation brightness is moderate.

Cavitation consists of big bubbles, so it contains small surface area per unit volume. Light reflection is low.

Cavitation brightness is clear.

Cavitation consists of small bubbles, so it contains large surface area per unit volume. Light reflection is high.

Backflow Cavitation

Weber No. $We = \frac{\rho_L u^2 D}{\sigma}$

No. 18

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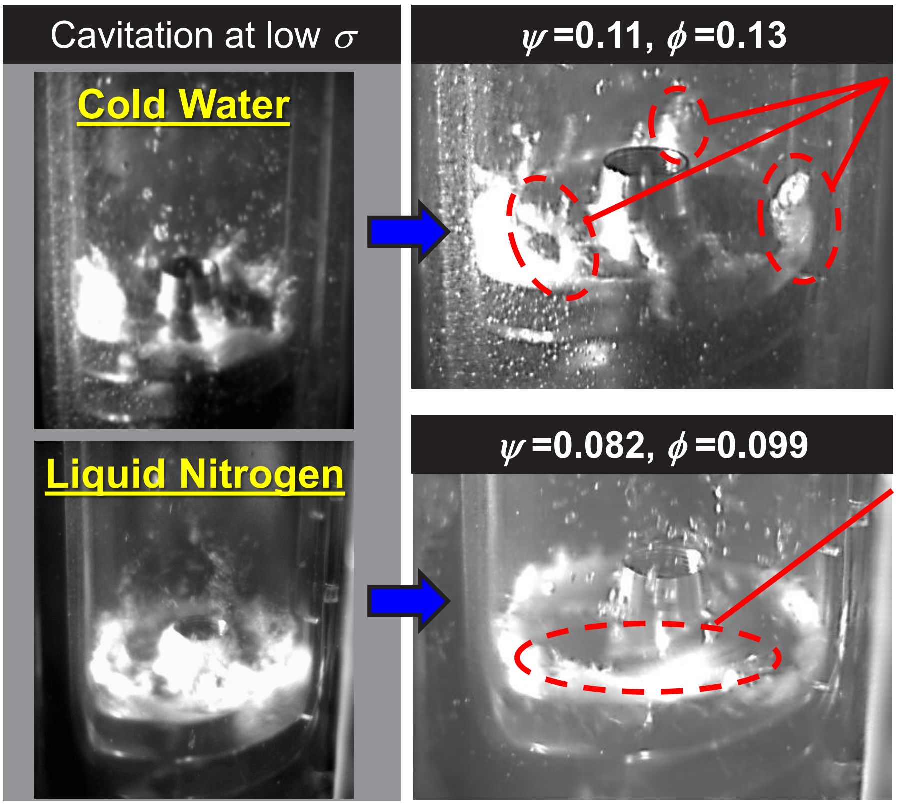
Linearly stretched backflow cavitation is not observed in cold water but in liquid nitrogen.



There are lots of linearly stretched backflow cavitation.

Higher Weber number of each cavitation bubble due to a bigger bubble

There is not linearly stretched backflow cavitation.

Lower Weber number of each cavitation bubble due to a smaller bubble

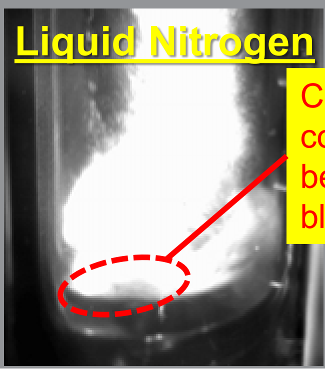
No. 19

Water Pump Falls into Breakdown, But Nitrogen Pump Still Works.

Big water bubbles can not condense, but small liquid nitrogen bubbles can condense.

Cavitation at $\sigma \approx 0$

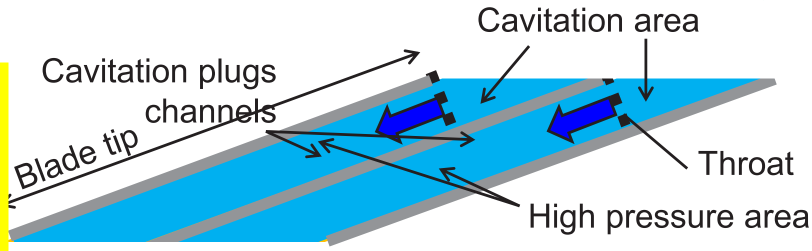
Cavitation plugs channels between blades.



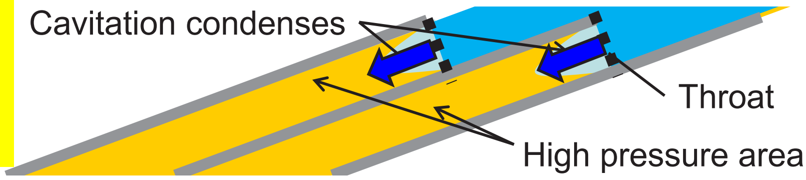
Cavitation condenses between blades.

Developed figure along blade tips

When the cavitation crosses the throat...,



Cavitation plugs channels between blades because cavitation bubbles are big. Therefore, the pump does not work.



Cavitation condenses between blades because cavitation bubbles are small. Therefore, the pump works.

No. 20

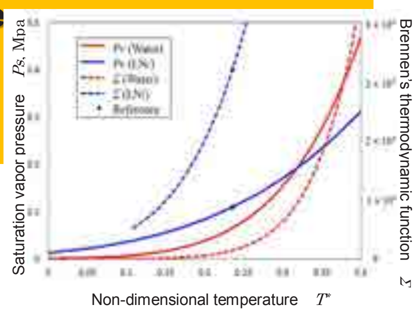
Cavitation on the Hub

There are some cavitation on the hub in liquid nitrogen, but there no cavitation in water.

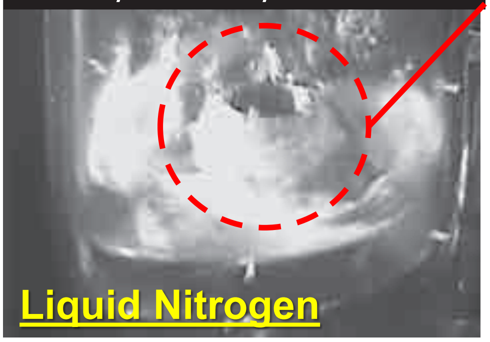
ψ=0.11, ϕ=0.11

There is no cavitation.

45.1K increase of temperature is required to genarate cavitation at stationary flow region. It is because there is the flat gradient of saturation vapor pressure curve at the lower non-dimensional temperature T^*.



ψ=0.17, ϕ=0.12



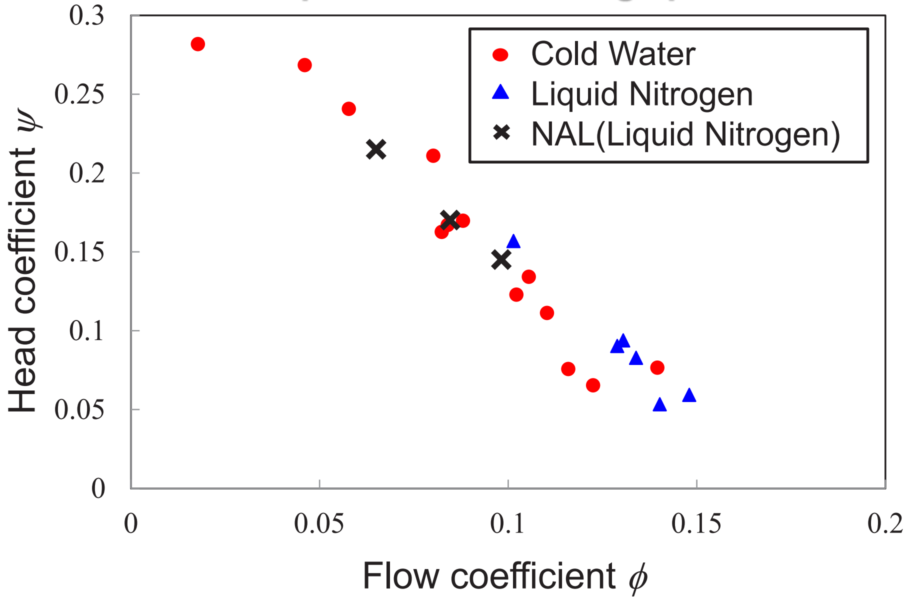
There are some cavitation on the hub.

Just 0.6K increase of temperature is required to genarate cavitation at stationary flow region. It is because there is the steeper gradient of saturation vapor pressure curve at the higher non-dimensional temperature T^*,

Performance Curve

No. 21

ϕ-ψ curve depends only on inducer geometry in non-cavitating condition. This curve is independent of rotating speed and a variety of fluids.



Flow Coefficient ϕ

$$\phi = \frac{Q}{A R_T \Omega}$$

Head Coefficient ψ

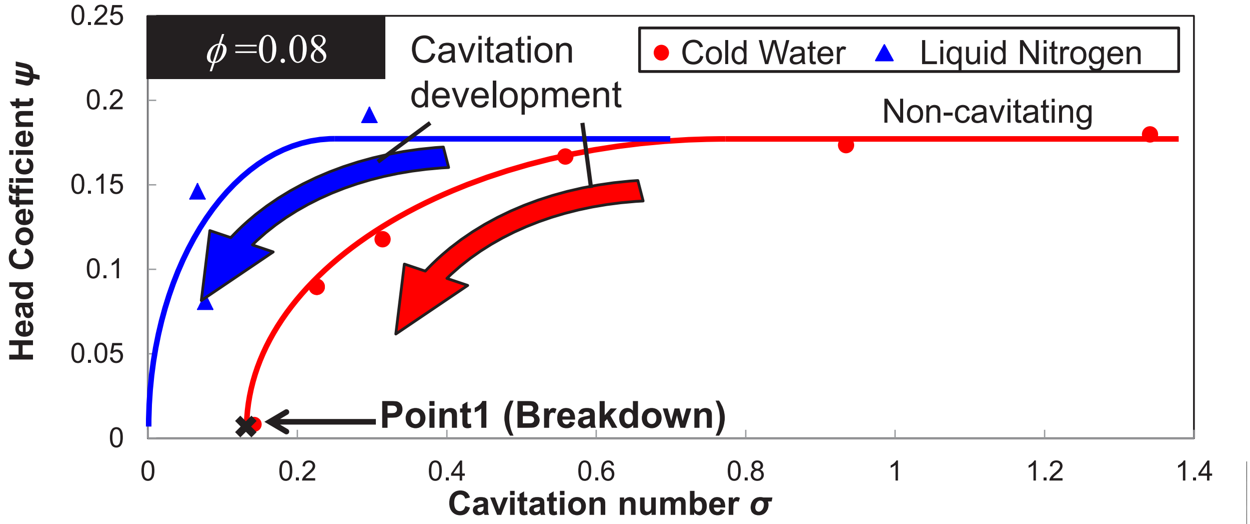
$$\psi = \frac{\Delta P}{\rho_L R_{T_2}{}^2 \Omega^2}$$

Q : Flow rate, m^3/s
A : Crosssectional Area, m^2
R_T : Tip radius, m
Ω : Angular speed, rad/s
ΔP : Head, Pa
ρ_L : Liquid density, kg/m^3

The data are a little bit scattering along the performance curve corresponding to the previous experiments by NAL (present JAXA). It means that the measured data are not sufficient, but not bad.

Cavitation Performance Curve at Constant Flow Coefficient

No. 22



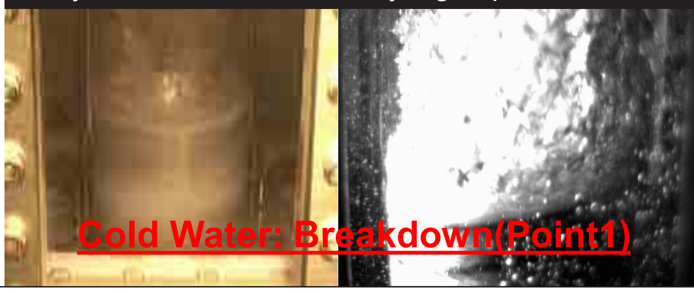
Cavitation Number σ

σ is index of cavitation possibility.

$$\sigma = \frac{p_1 - p_v}{\frac{1}{2}\rho_L U^2}$$

p_1 : Inlet static pressure
p_v : Saturated vapor pressure
U : Tip blade velosity ($R\Omega$)

By normal camera | By high-speed camera



No. 23

Conclusion

As a result, the following three results were obtained.

- The same performance curve in liquid nitrogen and water at 6000 rpm is obtained as previous experimental results by NAL (present JAXA) using the same inducer in liquid nitrogen at 16500 rpm. It means that measured pump heads and flow rates are not bad.

- Liquid nitrogen cavitation consists of much smaller bubbles than the water cavitation bubbles. The small bubble cavitation may cause "thermodynamic effects," which decrease cavitation number or NPSH at cavitation breakdown compared with water values.

- Only in liquid nitrogen experiments, hub cavitation occurs. At the higher non-dimensional temperature T^*, there is the steeper gradient of saturation vapor pressure curve. In addition, at the higher T^*, there is the larger Brennen's thermodynamic effect function Σ, namely, fluid has the greater thermodynamic effect. Therefore, in cases of fluid with greater thermodynamic effect, hub cavitation more easily occurs due to heat inflow.