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Several sample *Synoptics* have appeared in the August, September, and September-October issues of the Journals. The Publications Committee will discuss the implementation of *Synoptics* into the Journal structure at its October meeting. As soon as possible, *please send your suggestions or comments (positive or negative)* to Dr. Jerry Grey, Vice-President, Publications, at AIAA, 1290 Sixth Avenue, New York, N. Y. 10019 so that the Publications Committee will be able to consider your views in its deliberations.

SYNOPTIC: A Water-Augmented Air Jet for the Propulsion of High-Speed Marine Vehicles,

Rolf K. Muench and Allen E. Ford, Naval Ship Research and Development Laboratory, Annapolis, Md.; *Journal of Hydronautics*, Vol. 4, No. 4, pp. 130-135.

Marine Propulsion, Multiphase Flows, Propulsion System Hydrodynamics, Surface Vessel Systems

Theme

An analysis of a two-phase marine propulsion system is presented. The analysis includes the momentum transfer between the air and water particles, the shattering of the particles by the air stream, losses due to heat transfer between the phases, wall friction, etc. Thrust data from a small-scale static experiment are shown to agree with the theoretical predictions over the range of water-air mass flow tested.

Content

The water-augmented air jet or mist jet employs the bypass air of a turbofan as its air source. Water scooped from the sea is injected through spray nozzles into the bypass air and the mixture is expanded in a two-phase nozzle. The system is lightweight and therefore suited for propulsion of weight sensitive high-speed marine vehicles. The mist jet, although lighter and cheaper, unfortunately, is less efficient than the competing systems, but from an economic standpoint the lighter weight, lower-cost mist jet can overcome its efficiency handicaps at speeds in excess of 75 knots.

The water pressure available for spraying is the portion of freestream stagnation pressure recovered by the high-speed inlet, less the water lift to the spray station, piping, and spraying losses. At low ship speeds the low water pressure cannot establish flow against the air pressure at the spray station. Relying on the inlet recovery to provide the spray pressure and avoiding the high cost in weight and power of a water pump, requires the unaugmented thrust be sufficient to accelerate the ship to the speed where augmentation is possible.

The thrust augmentation of the mist jet is due to the increased mass flow at constant power input which decreases the exit velocity by conservation of momentum resulting in lower kinetic-energy losses to the wake. This augmentation in thrust is not accomplished without losses as mentioned in the preceding paragraph.

The theory developed to predict the performance of the

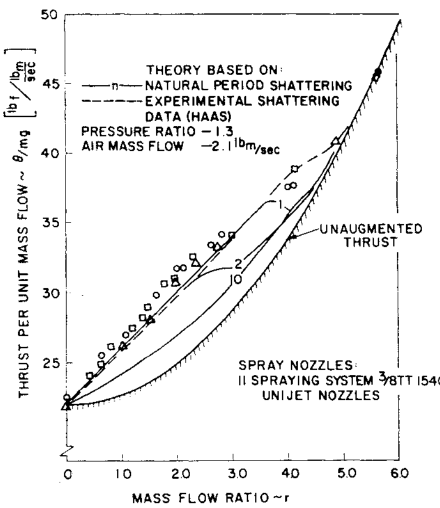

Fig. 1 Experimental and analytical results for first spray station configuration.

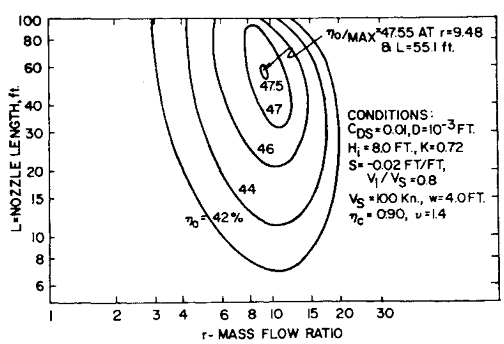

Fig. 2 Efficiency map.

mist-jet system includes: 1) inlet, compression and injection losses; 2) inlet drag; 3) expansion of the water particle-air continuum mixture; 4) heat transfer between water particles and air; 5) shattering of water particle during the expansion; 6) wall friction.

This theory agrees with the results of a small experiment as shown in Fig. 1. The experiment consists of a 4-ft expansion nozzle with a 32-in^2 inlet area.

The performance of a 4- $\times$ 8-ft inlet area, 100-knot mist jet is shown in Fig. 2. In order to reach optimum efficiency relatively long nozzles are required. Shorter nozzles are possible at only a small sacrifice in efficiency.

A Water-Augmented Air Jet for the Propulsion of High-Speed Marine Vehicles

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An analysis along with results of a small-scale, static experiment are presented. The analysis includes the effect of momentum transfer between the air and the water particles, the shattering of the particles exposed to an air stream, losses attributed to heat transfer between the air and the water, wall friction, etc. The experimental thrust data are shown to agree with the theoretical predictions over the entire range of water-air mass flow tested. The performance of this propulsion system is examined as a function of ship speed, nozzle length, etc.

Nomenclature

A = two-phase nozzle cross-sectional area
A_s = water inlet cross-sectional area
C = liquid-phase specific heat
C_p = gas-phase specific heat
C_D = particle drag coefficient
C_{DS} = inlet drag coefficient
D = particle diameter
D_H = hydraulic diameter
D_S = inlet drag
F_D = particle drag force
h = heat-transfer coefficient
H_i = initial nozzle heights
K = freestream dynamic pressure recovery coefficient
L = nozzle length
$\dot{m}$ = mass flow rate
Nu = Nusselt number
P = static pressure
r = mass flow ratio
R = gas constant
Re = Reynolds number
q = particle heat transfer
S = two-phase nozzle slope
$\hat{T}$ = characteristic particle shattering time
$\hat{T}_H$ = characteristic particle shattering time according to Haas[13]
T = temperature
T_i = initial or ambient temperature
V = velocity
w = two-phase nozzle width
We = Weber number
X = two-phase nozzle coordinate
γ = ratio of specific heats
η_c = compressor efficiency
η_0 = propulsion efficiency
ν = stagnation pressure ratio
ρ = density
σ = liquid-gas velocity ratio
θ = thrust
τ_w = two-phase wall shear

Subscripts

Ex = exit condition
g = gas phase
ℓ = liquid phase
S = ship condition

Introduction

THE water-augmented air jet or mist jet is a reliable, lightweight, high-speed marine propulsion system, utilizing a two-phase propulsion fluid. That is, a mixture of water and air, both of which are plentiful at the ocean surface, is expanded through a nozzle to produce thrust. The process is properly referred to as augmentation since the air jet is capable of producing thrust by itself.

The concept of two-phase propulsion is not new in the marine propulsion field. Past efforts have primarily been centered on the hydroramjet,[1] its pulse-jet cousin, and the liquid ejector using either compressed air or steam.[2] In general, these systems suffer from high heat-transfer losses to the water, since they use either adiabatically compressed high-pressure air or combustion products. Others fail to provide zero velocity thrust and thus require auxiliary propulsion power plants.

The water-augmented air jet is a more recent addition to the two-phase marine-propulsion field. It represents an improvement over the other systems since it is partially able to overcome some of their problems, such as excessive heat-transfer losses and the lack of static thrust. Preliminary studies of this concept were published by Muench and Keith[3] and Davison and Sadowski.[4]

It has been mentioned that the mist jet is a lightweight system. This is basically a result of eliminating mechanical transmission elements and using aircraft-type power plants. This system employs a turbofan which is usually designed for subsonic speed (500 knots). By injecting water in the form of particles into the bypass air, the system is suited for propulsion of prospective high-speed marine vehicles. The turbofan and associated equipment for injecting water and the two-phase expansion nozzle are still light compared to the water jet and super-cavitating propeller. The bypass air of the turbofan, with a pressure ratio between 1.3 and 1.5, is especially suited, since the efficiency of the mist jet decreases

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