Study of Cycle Output Improvement by Working Fluid Including Phase Change Material (Postprint)

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Abstract

This paper represents numerical simulation of flow inside an axial transonic compressor subject to inlet flow distortion, to evaluate its effect on compressor performance and stability. Two types of inlet distortion, namely inlet swirl and total pressure distortion are investigated. To study the effect of combined distortion patterns, different combinations of inlet swirl and total pressure distortion are also studied. Results for cases with total pressure distortion indicate that hub radial distortion improves stability range of the compressor while tip radial distortion deteriorates it. An explanation for this observation is presented based on redistribution of flow parameters caused by distortion and the way it interacts with stall inception mechanisms in a transonic axial compressor. Results also show that while co-swirl patterns slightly improve stability range of the compressor, counter-swirl patterns diminish it. Study of combined distortion cases reveals that superimposition of effects of each individual pattern could predict the effect of a combined pattern on compressor' s performance within an accuracy of 1%. However, it is unable to predict the associated effect on compressor' s stability.

Full Text

Preamble

Study of Cycle Output Improvement by Work-Fluid Including Phase Change Material

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Abstract

This paper investigates output improvement in heating and cooling cycles using work-fluid containing phase change material (PCM). The experimental study examines heat exchange between the work-fluid and heat transfer surfaces, where the work-fluid flows to high- or low-temperature heat transfer surfaces through a narrow path. To enhance heat transmission, a trace amount of Diethylether (boiling point 34.8 °C) is added to the work-fluid as a PCM. Experimental parameters include the PCM additive amount, displacer piston rotational speed, and heat transfer surface temperature. The results clarify that PCM addition increases engine cycle output. The effect of PCM addition is evaluated using an output ratio defined from experimental cycle output data, and the requirements for achieving output enhancement through PCM addition are identified.

Keywords: Phase change material, Heat transfer, Output improvement, Low temperature difference engine

Introduction

Low-temperature heat (less than 100°C) from factory exhaust or hot springs is largely discarded and remains underutilized. Japan alone has more than 3,000 hot spring resorts with accommodation facilities [1]. While electricity generation using binary cycles [2] or thermoelectric conversion elements [3] is being attempted in some locations, equipment construction involves substantial costs. Generating output from low-temperature heat energy requires installing expensive, large-scale equipment, with system enlargement driven by the need to expand heat exchange components and other elements. Consequently, cost recovery demands a long period of selling generated electricity.

The ultimate goal of this research is developing a low-temperature difference drive engine for small-scale power generation in hot spring resorts, where travelers can observe its operation. To achieve this visual appeal, the engine operates at low rotational speeds. This study targets the Stirling cycle, which maintains high efficiency even at small scales. Such engines feature simple structures, low cost, and easy maintenance. However, obtaining sufficient output is challenging due to the low temperature difference.

The authors previously discovered that adding a small amount of phase change material—with a boiling point between the high- and low-temperature sources—to the work-fluid increases engine output [4]. This paper examines cycle output enhancement using work-fluid containing phase change material, where the work-fluid flows into heating or cooling surfaces through a narrow path during the cycle. While previous studies [5-7] evaluated work-fluid heat transfer using single-phase gas, this research adds a small quantity of Diethylether (C H O, molecular weight 74.12 g/mol, density 0.7134 g/cm^3 in liquid phase, boiling point 34.8°C, colorless liquid) as a phase change material to the base work-fluid (air). The study presents experimentally estimated stable drive cycle output results under parameters of 5-20 r/min rotational speed, 45-60 K heat source temperature difference, and 0-4 mass% PCM mass composition ratio. The findings are presented as a useful experimental correlation equation.

Nomenclature

Symbol	Definition
S (=Wh×D)	Coefficient
Add	Mass additional ratio to Air (mass%)
C	Coefficient
Cp	Specific heat (J/(kg · K))
D	Depth (m)
G	Mass (kg)
H	Height between displacer piston and heat transfer surface (m, mm)
L	Length (m)
N	Number of revolutions (r/min)
n	Number of times (-)
P	Pressure (kPa)
ΔP	Pressure difference (kPa)
Q	Exchange heat per time (J/s)
Qh	Exchange heat on heating process (J/cycle)
S	Area of heat transfer surface (m^2)
St	Stroke (60 mm)
t	Time (s)
T	Temperature (°C)
ΔT	Temperature difference of heat source (K)
ΔT^*	Temperature difference ratio (-)
umc	Mean velocity on heat transfer surface (m/s)
V	Volume (m^3, mL)
W	Output power (J/cycle)
W^*	Output power ratio (-)
	Kinematic viscosity (m^2/s)
	Rotation angle (rad)
	Thermal conductivity (W/(m · K))

Subscripts:
cycle - Cycle process
bp - Boiling point
d - Displacer piston
step - Data step
f - Work-fluid (Air, Air+PCM)
h - Heating
c - Cooling

i - Initial
PCM - PCM including

Experimental Apparatus and Procedure

Experimental Apparatus

Fig. 1 shows the schematic diagram of the experimental apparatus, which consists of a test section, an actuator, a data logger, and two constant temperature baths. The test section is constructed from clear acrylic resin with 10 mm thick thermal insulation panels adhered to its internal surfaces. The inner dimensions are 120 mm in height, 300 mm in width, and 150 mm in length. The upper and bottom surfaces are 3 mm thick copper plates serving as the cooling and heating areas, respectively. Temperatures are measured at six points on each surface using K-type thermocouples (0.18 mm diameter), with surface temperatures controlled within ±0.2 K of experimental conditions. Pressure changes are measured by a pressure sensor (Keyence AP-43, range 0–1.000 MPa, resolution 0.1 kPa, response time 1 ms) mounted on the acrylic test section wall. PCM is introduced using a digital burette (Continuous E, 2.5 mL/rev., minimum scale 0.01 mL, accuracy ±0.2%). A displacer piston inside the test section connects to an actuator (Misumi single-axis robot RSD2, position accuracy ±0.02 mm, maximum load 25 kg, stroke 50–300 mm) via a SUS seal rod (3 mm diameter) and moves vertically under computer control. Upward piston movement increases test section pressure, forcing upper work-fluid to the bottom side. Pressure increases through heat exchange between work-fluid and hot heat transfer surface, while downward piston movement decreases pressure. The heat exchange cycle experiment is conducted under each condition, with work-fluid passing through 3 mm gaps (150 mm length) in the side wall via piston motion. The piston stroke is 60 mm.

Thermophysical Properties of Test Work-Fluid

The work-fluid is either air or an air-diethylether mixture. Diethylether is selected as the PCM due to its boiling point falling between the heating and cooling surface temperatures. Table 1 presents thermophysical properties of air and diethylether. For example, 1.0 mass% addition at 24°C corresponds to 0.1114 mL or 0.07953 g of diethylether.

Experimental Procedures

The heat exchange cycle experiment follows these procedures:

1. Exhaust residual work-fluid from the test section using a vacuum pump.
2. Introduce air at 24°C and 101.3 kPa (absolute humidity 0.0112 ± 0.0007 kg/kg*) into the test section, then inject specified quantities of diethylether using the digital burette.
3. Set cooling and heating surfaces to experimental condition temperatures.
4. Initiate upward displacer piston motion from the bottom side and continue the heat exchange cycle until pressure variation reaches stable cycles. At this point, measure and collect pressure, heat transfer surface temperature,

and work-fluid temperature data in the data logger.

Experimental Conditions

Table 2 summarizes the experimental conditions. Heat source temperature difference is set at 55-70 K, encompassing the PCM boiling point. The high-temperature source is maintained below 80°C to simulate hot spring conditions, while the low-temperature source is held at 10°C. Displacer piston speed is set to low-speed rotation N = 5-20 r/min (umc = 0.2-0.9 m/s). The PCM (diethylether) mass composition ratio in the work-fluid (air) is evaluated at Add = 0-4 mass%.

Fig. 2 shows the time history of displacer piston position and velocity. Piston position is determined by rotation angle regardless of revolution number, with sine wave operation performed in the cycle process to mimic actual engine control by rotation angle. The computer-controlled actuator operates the displacer piston, yielding heating process times of 1.5 seconds at 20 r/min, 3.0 seconds at 10 r/min, and 6.0 seconds at 5 r/min.

Results and Discussions

Indicator (ΔP-V) Diagram and Cycle Velocity

Fig. 4 shows the pressure difference versus heating side volume relationship (indicator ΔP-V diagram) at Add = 0 mass% (air), N = 20 r/min, and ΔT = 50 K. Cycle pressure increases from the experiment start, with stable cycles centered on 0 kPa observed at n   22.

Fig. 3 illustrates the variation of cycle mean velocity on the heat transfer surface with revolutions, showing a linear relationship. The cycle mean velocity is estimated using Reynolds number Re based on averaged flow velocity for each revolution, with characteristic length set to half the heat transfer surface width (L = 0.15 m) since work-fluid flows from both ends toward the center. Air’ s dynamic viscosity is used for calculation due to the minimal PCM addition amount.

Cycle Output Using Air as Work-Fluid

Fig. 6 shows output per cycle versus revolutions at Add = 0 mass% (air). Cycle output decreases with increasing revolutions due to reduced heat exchange time. Fig. 7 presents output per cycle versus heat source temperature difference at Add = 0 mass% (air), demonstrating that cycle output increases with temperature difference.

The experimental data for air (Add = 0 mass%) is correlated by the following equations, which reproduce experimental data within ±10%:

For 5   N   20:

$$W = -0.012N + 0.34 \quad (12)$$

For 45 ΔT 60:

$$W = 0.008\Delta T - 0.15 \quad (13)$$

For 45 ΔT 60:

$$W = 0.008\Delta T - 0.15 \quad (14)$$

Cycle Output Using Air-PCM Mixture as Work-Fluid
Fig. 8 shows the relationship between output per cycle and cycle time or revolutions at Add = 0.5 mass%. Output per cycle decreases with increasing revolutions. Fig. 9 presents output ratio variation with temperature difference ratio at N = 15 r/min (Re = 6870). Experimental values (plots) are compared with correlation equation predictions (lines), showing high output ratios in the range ΔT* = 0.8-1.2.

Fig. 10 illustrates the relationship between output ratio and Reynolds number or revolutions at T* = 1.2, revealing high output ratio in the range Re = 4945-6870 (N = 10-15 r/min). Fig. 11 shows output ratio versus PCM addition ratio at Re = 6870 (N = 15 r/min), with high output ratios observed at Add = 0.5-1 mass%.

The output ratio W* is correlated by Add, ΔT*, and Re, yielding the following equation with applicable range: Re = 4945-8643 (N = 10-20 r/min), ΔT =* 0.8-1.2 (ΔT = 45-55 K), and Add = 0.5-3 mass%.

$$W^* = 1.2 \cdot \mathrm{Add}^{0.2} \cdot \Delta T^{*0.5} \cdot \mathrm{Re}^{-0.1} \quad (15)$$

Conclusions

This experimental study of heat exchange cycles using PCM-containing work-fluid (diethylether) yields the following conclusions:

- Output improvement through PCM addition to work-fluid was observed in the heat exchange cycle.
- The optimum condition range (PCM mass composition ratio, speed, and temperature) for cycle output improvement was identified.
- A useful experimental correlation equation for cycle output ratio was proposed.

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Note: Figure translations are in progress. See original paper for figures.

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