DEVELOPMENT OF AN INDUSTRIAL STEAM GENERATION HEAT PUMP USING A LOW GWP REFRIGERANT

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ABSTRACT

The industrial heating process has conventionally used steam generated by combustion of fossil fuels for heat treatment in heating, drying, sterilization, and other processes. To decarbonize and electrify the steam generation process, an industrial steam generation heat pump that uses a low GWP refrigerant which is also non ozone depleting, and has low flammability and toxicity was developed.

Keywords: steam generation heat pump, Low GWP refrigerant, Decarbonization, Electrification

1. INTRODUCTION

Japan aims to achieve carbon neutrality (CN) by 2050 and is working to decarbonize its energy supply and demand structure and promote thorough energy conservation. Heat pump technology is expected to play an important role in electrification at high temperatures in the industrial sector. Wide use of heat pump technology is an important pillar for the achievement of Japan's carbon neutrality, as it enables a significant reduction of CO_2 emissions in the heat sector if pursued in parallel with the decarbonization of electricity.

In the industrial sector such as factories, steam boilers are widely used to generate heat used in various heating applications such as water heating, cleaning, sterilization, drying, boiling, steaming, fermentation and brewing, direct heating, etc., with a high demand for heat below 200 °C.

If a steam generation heat pump capable of generating steam above 140 °C is developed as an alternative to steam generated by fossil fuel combustion, it would be possible to construct all-electric and boiler-less factories. Steam generation heat pumps are currently available in Japan, but they are limited to system applications that use refrigerants with high global warming potentials of 1000 or more, resulting in large environmental impacts. This project, therefore, aims to develop an industrial steam generation heat pump that can supply high temperatures using a green refrigerant with low environmental impact, and promote energy conservation and electrification of factories with high heating demand.

2. STEAM GENERATION HEAT PUMP SYSTEM OVERVIEW

(1) System flow

The system is mainly divided into two parts, the steam generation heat pump and flash tank. The main components of the heat pump part are the compressor, condenser, sub cooler (1) (for heating supply water to the flash tank), sub cooler (2) (for providing water for process heating), liquid-gas heat exchanger, expansion valve and evaporator.

As shown in Fig.1, the refrigerant in the heat pump exchanges heat with heat source water in the evaporator and evaporates, the evaporated refrigerant then flows to the liquid-gas heat exchanger where it is further heated by the hot refrigerant liquid to ensure superheated refrigerant enters the compressor. In the compressor, the refrigerant gas is compressed to high temperatures and pressure before being sent to the condenser. In the condenser the refrigerant exchanges heat with hot water from the flash tank and condenses. The condensed refrigerant further exchanges heat with supply water in sub cooler (1) and sub cooler (2) before being sent to the liquid-gas heat exchanger where again it is further sub cooled. The sub cooled refrigerant flows to the expansion valve where it is expanded to low temperatures and pressure before being sent to the evaporator again.

Hot water held in the flash tank is supplied to the condenser by a pump. Hot water exchanges heat with the refrigerant in the condenser and its temperature is elevated before being returned to the flash tank. In the flush tank, steam is generated. Steam generated in the flush tank is supplied for process heating from the top of the tank while the remaining hot water is stored at the bottom of the tank and resupplied to the condenser for reheating.

During process heating, the amount of hot water in the flash tank decreases because steam is generated and supplied form the tank. To control the amount of hot water in the flash tank during steam generation, supply water of the same volume as the amount of steam supplied from the flash tank is supplied to the flash tank after being heated in sub cooler (1).

The system can also generate hot water for processing heating in sub cooler (2) while simultaneously generating steam. The temperature of hot water from sub cooler (2) and the amount are independently controlled.

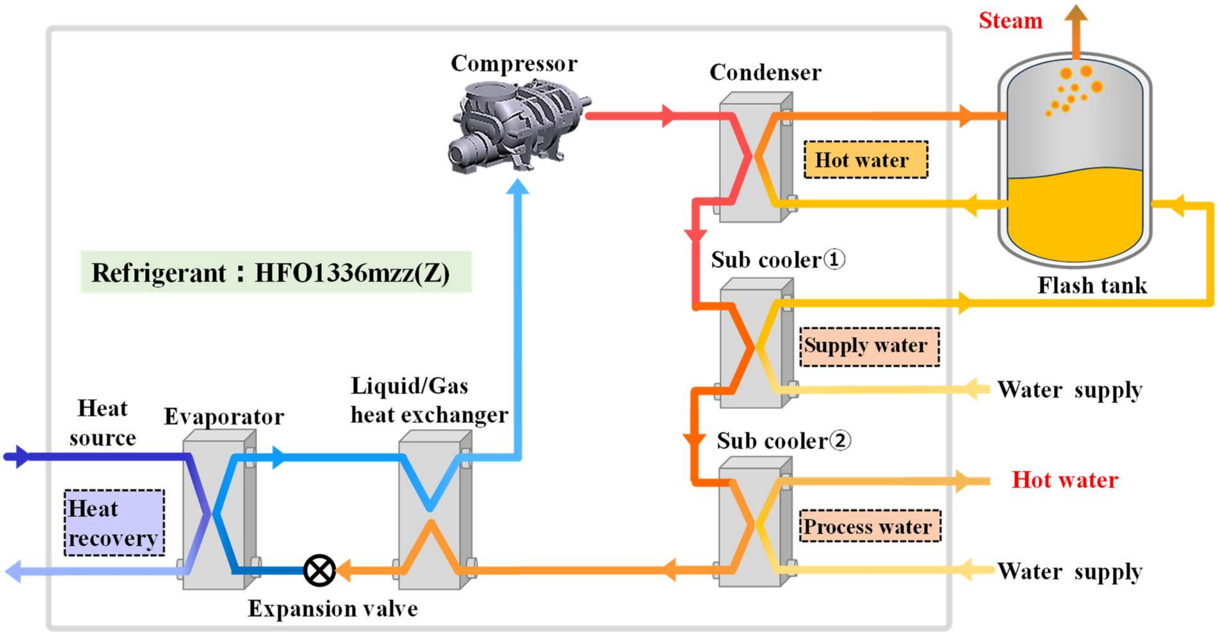

Fig.1 Steam Generation System

Figure 1 shows a simple flow of the steam generation system. The heat pump, on the left side of figure 1 is housed in a machine casing (components within the grey rectangle), while the flash tank is installed outside the machine casing. Supply water to the sub coolers, hot water to the condenser and heat source water to the evaporator are connected to the heat pump by piping.

Figure 2 shows an external view of the unit.

Fig.2 Unit Exterior Appearance

(2) System specifications

The heat pump system uses HFO1336mzz(Z) as the refrigerant to recover heat from the source water and dissipate it in the condenser to produce hot water for steam generation. HFO1336mzz(Z) is used because of its low environmental impact and high safety. A standard screw compressor was modified with special specifications to satisfy the high temperature requirements needed for steam generation heat pumps using this refrigerant. The maximum discharge temperature of the compressor is 180°C.

The design conditions are to supply 140°C steam at 300 kg/h with a condensation temperature of 150°C and an evaporation temperature of 75°C, with a target COP of 3.0. Heating capacity is defined as the total amount of heat derived from the condenser, sub cooler (1) and sub cooler (2).

To satisfy the conditions mentioned above, a standard model compressor was selected and modified. The main heat pump components, the evaporator, condenser, sub coolers, liquid-gas heat exchanger, expansion valve and flash tank were designed and fabricated. Table 1 shows the heat pump specifications.

Table 1 Heat Pump Specifications

Item		Conditions/Specifications
Type		Water source steam generation heat pump
Refrigerant		HFO1336mzz(Z)
Comp.	Type	Oil-injected screw
	Specification	Max. discharge temp.180℃
Steam generation		Flush tank method
Design conditions	Cond. Temp.	150℃
	Eva. Temp.	75℃
	Heat capacity	200～300kW
	Steam temp.	140℃
	Steam flow rate	300～350kg/h
	Target COP	3.0

3. TEST METHOD

To verify the performance of the steam generation heat pump, a test facility was fabricated. The test facility was designed to test the performance of the heat pump system under various conditions of condensation and evaporation temperatures, refrigerant and water flow rates of both sources. Table 2 shows temperature conditions under which tests were conducted.

Table 2 Test Temperature Conditions

Item	Conditions
Condensation temperature	115～150°C
Evaporation temperature	50～75°C
Suction superheat temperature	17～42°C
Heat source water temperature	60～90°C
Steam temperature	110～140°C

Heat capacities on the refrigerant side of the heat pump system as well as the steam side of heat generation system were calculated as the product of the enthalpy differences Δh [kJ/kg] and mass flow rates in each component of the system. The enthalpies were calculated from the measured values of the pressures and temperatures measured at the inlet and outlet of each component and the flow rate was measured by a flow meter. The capacities at the water side were calculated from measured temperatures at the inlet and outlet of the heat exchangers, calculated mean specific heat [kJ/kg-K] over the heat exchangers and water mass rate [kg/s] measured by flowmeters. The Compressor power [kW] was measured by an electric meter.

4. TEST RESULTS

(1) Design condition test results

Figure 3 shows the test results under design conditions.

When operated under the following conditions: heat source water inlet temperature of 86°C, heat source water outlet temperature of 79°C, and supply water inlet temperature of 81°C for sub coolers (1) and (2), the flash tank could supply 330 kg/h of steam at 140°C and sub cooler (2) could supply 6.4 t/h of hot water at 92°C. In this case, the total heating capacity of the condenser, sub coolers (1) and (2) was 317 kW, while the compression power was 107 kW and the heating COP was 3.0. It was, therefore, confirmed that this system can provide a stable supply of 140°C steam.

The system shown in Figure 3 can generate steam and hot water simultaneously, but there may be cases where hot water is not required. Figure 4 shows test results when sub cooler (2) is not used.

When the system was operated under the following conditions: heat source water inlet temperature of 85°C, heat source water outlet temperature of 80°C, and sub cooler (1) supply water inlet temperature of 80°C. The flash tank was able to supply 362 kg/h of 140°C steam. Although the total heating capacity and heating COP are lower than those of the system shown in Figure 3, it was confirmed that stable operation is possible even with a system requiring steam only.

(2) Variable temperature condition test results

Tests were conducted to confirm changes in heating capacity and steam supply when evaporation and suction superheat temperatures were varied.

Figure 5 shows test results at various evaporation temperatures, while Figure 6 shows results at various suction superheat temperatures.

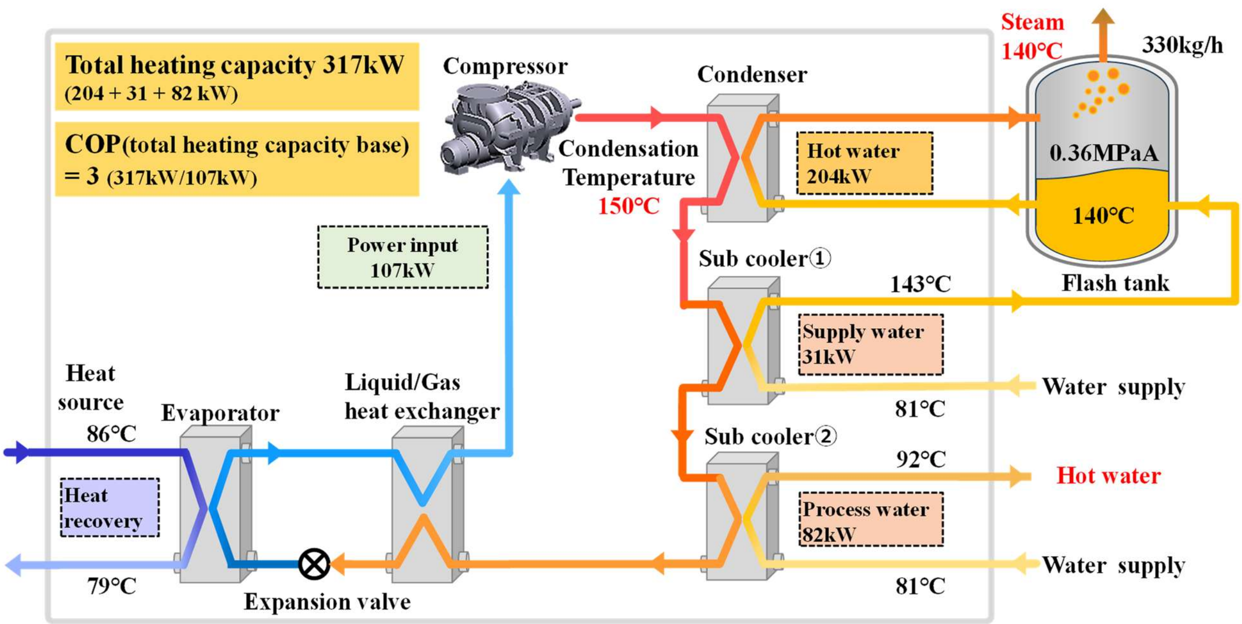

Fig.3 Test results under design conditions

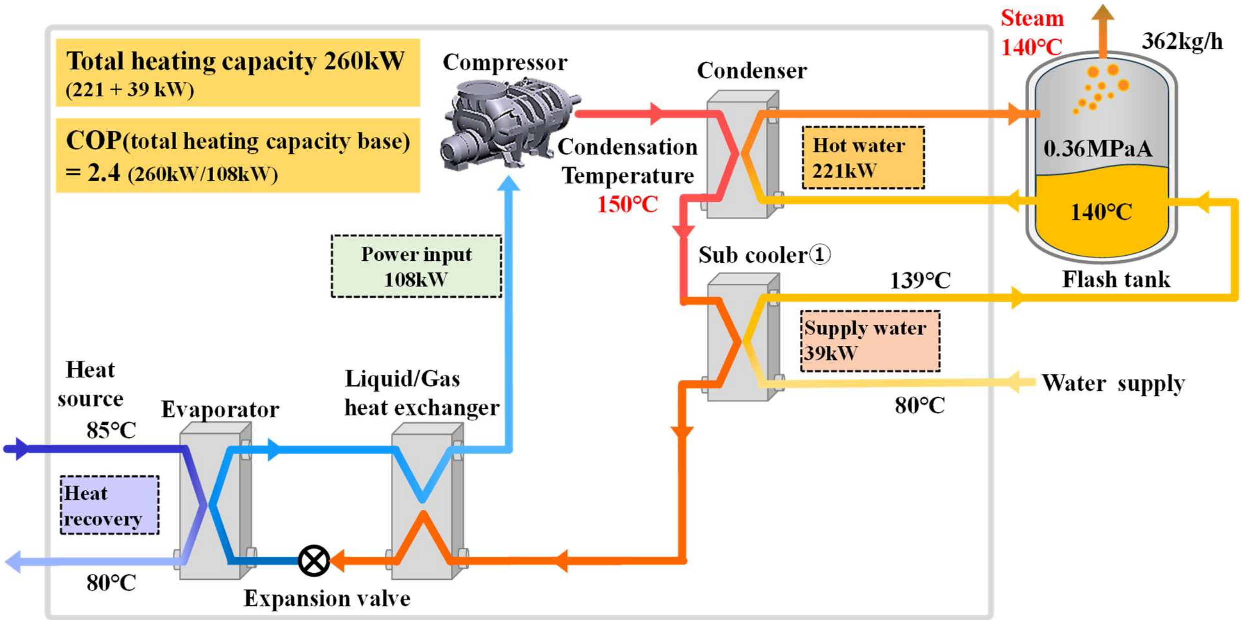

Fig.4 Test results under design conditions (Sub cooler (2) not used)

With various evaporation temperature tests, the heating capacity ranged from 110 to 216 kW while steam supply rate varied from 179 to 358 kg/h. The evaporation temperatures varied from 51 to 78°C while steam supply was kept at 140°C. Under the experimental conditions mentioned above, increments in evaporation temperatures of 3 to 5℃ resulted in an increase in heating capacity and steam supply rate of 10 to 15%. As a result, the heating capacity and steam supply at the evaporation temperature of 78°C were approximately twice as much as those at 51°C.

In various suction superheat temperature tests, the heating capacity ranged from 191 to 221 kW while steam supply ranged from 310 to 362 kg/h. Suction superheat temperature was varied from 17 to 42°C while steam supply was kept at 140°C. Increments in suction superheat temperatures of 3 to 5°C showed slight increments in heating capacities and steam supply rates, 2 to 5%.

Figures 5 and 6 show that high evaporation temperatures and compressor suction superheat temperatures give high heating capacities and steam supply rates.

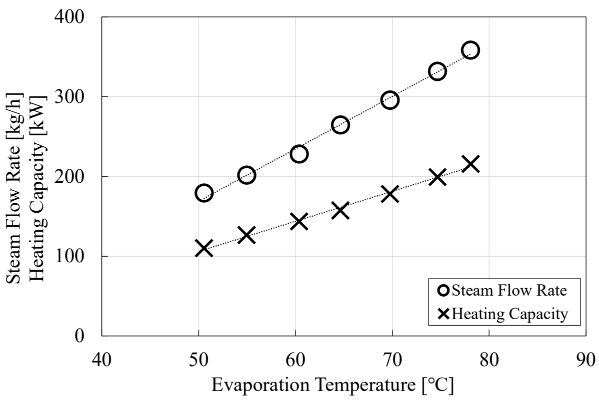

Fig.5 Evaporation temperature variable test result

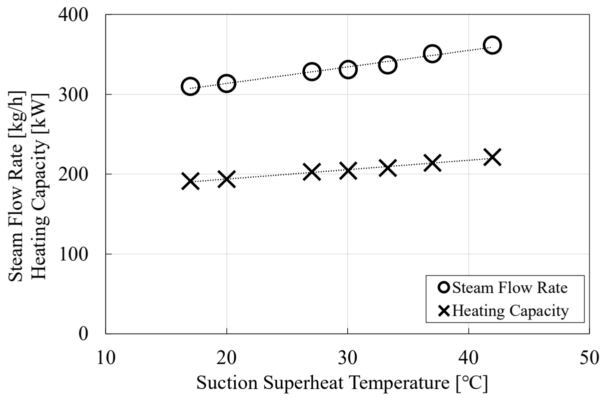

Fig.6 Suction superheat temperature variable test results

5. CONCLUSION

In this study, an industrial steam generation heat pump using a low GWP refrigerant HFO1336mzz(Z) was developed and experiments confirmed it can supply 140°C high temperature steam stably. In tests under design conditions, a heating COP of 3.0 was achieved, and it was demonstrated that the heat pump can also generate hot water for process heating at the same time. Changes in heating capacity and steam supply rate under various evaporation temperatures and compressor suction superheat temperatures were evaluated, and it was shown that system performance can be improved by optimizing the operating conditions.

This system is expected to be widely used as an environmentally friendly heating technology that replaces the conventional fossil fuel steam supply systems, contributing greatly to decarbonization, electrification, and energy conservation in the industrial field.

This paper is based on results obtained from project, JPNP21005, subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

低 GWP 冷媒を用いた産業用蒸気生成ヒートポンプの開発
Development of an industrial steam generation heat pump using a Low GWP refrigerant

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The industrial heating process has conventionally used steam generated by combustion of fossil fuels for heat treatment in heating, drying, sterilization, and other processes. To decarbonize and electrify the steam generation process, an industrial steam generation heat pump that uses a low GWP refrigerant which is also non ozone depleting, and has low flammability and toxicity was developed.

Key Word: steam generation heat pump, Low GWP refrigerant, Decarbonization, Electrification

１．はじめに

日本は2050年までにカーボンニュートラル(CN)を達成することを目指し，エネルギー需給構造の脱炭素化と徹底した省エネルギーの推進に取り組んでいる．その中でも，ヒートポンプ技術は重要な役割を担っており，特に産業部門における高温域での電化が注目されている．ヒートポンプ技術の普及は，電力の脱炭素化と並行して進めることで，熱分野における CO_2 排出量の大幅な削減を可能にし，日本の CN 達成に向けた重要な柱となっている．

工場などの産業分野では，200℃未満の熱需要が多く，給湯，洗浄，殺菌，乾燥，煮炊き，蒸し，発酵醸成，直接加熱等の様々なプロセス加熱においてボイラ蒸気が多く使用されている．現状，化石燃料の燃焼により生成された蒸気を使用しており，この代替として，140℃以上の加熱が可能なヒートポンプが開発されれば，化石燃料を用いたボイラを使用することなく蒸気供給が可能となり，オール電化，ボイラレスの工場構築も可能となる．また，現在，日本国内において蒸気生成ヒートポンプは販売されているが，温暖化係数が1000 以上と環境影響の大きい冷媒を採用した機器に限られている．本開発では環境影響の小さいグリーン冷媒を用いて高温供給が可能な産業用蒸気生成ヒートポンプを開発し，加熱需要の多い工場の省エネルギー，電化を推進する．

２．蒸気生成ヒートポンプシステム概要

(1) システムフロー

本システムは大きく分けると蒸気生成ヒートポンプとフラッシュタンクで構成されている．また，ヒートポンプの主要構成機器は，圧縮機，凝縮器，過冷却器①（フラッシュタンク補給水加熱），過冷却器②（プロセス加熱），液ガス熱交換器，膨張弁，蒸発器である．

ヒートポンプ本体は冷媒（高圧ガス）を用いて冷凍サイクルを形成している．蒸発器で熱源水と熱交換し蒸発した冷媒は，液ガス熱交でさらに加熱され圧縮機に送られる．圧縮機で高温・高圧に圧縮された冷媒ガスは，凝縮器でフラッシュタンクから送られる熱水と熱交換する．凝縮器で液化した冷媒は，過冷却器①と過冷却器②でさらに補給水と熱交換を行い，液ガス熱交換器，膨張弁を経て蒸発器へと送られる．このとき，フラッシュタンクに保有されている被加熱水は，フラッシュ

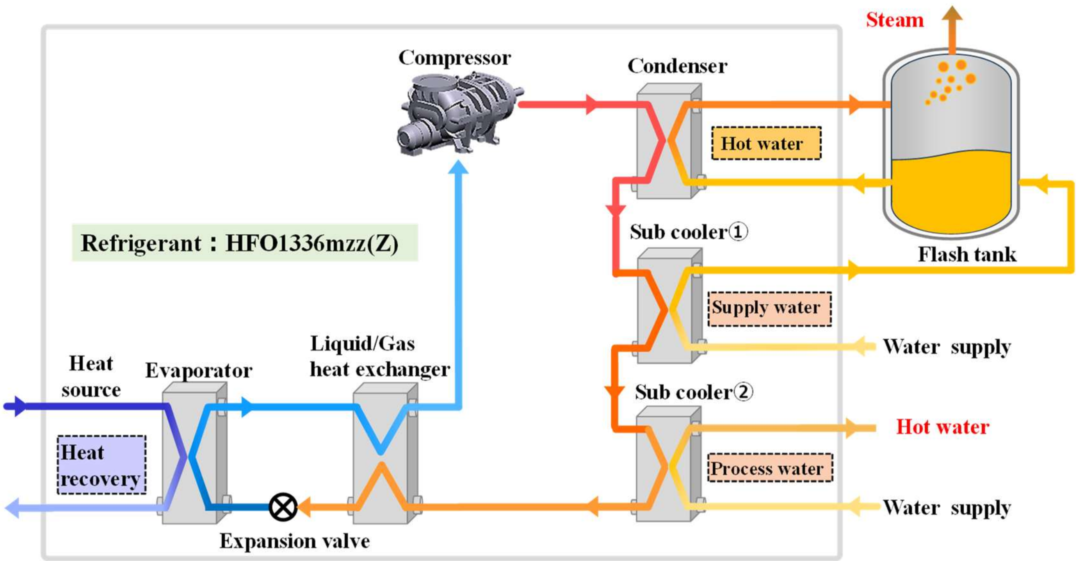

Fig.1　Steam Generation System

タンクから凝縮器へ送られ，凝縮器で冷媒により加熱され，フラッシュタンクに戻り，蒸気と熱水に分離される．そして、蒸気はフラッシュタンクの上部から供給，熱水はフラッシュタンク下部に溜められ，再び凝縮器へ送られる構造となっている．システム運転中，蒸気が供給されるとフラッシュタンク内部の被加熱水保有量が減少する．フラッシュタンク内の被加熱水保有量をコントロールするため，フラッシュタンクから供給された蒸気量と同量の補給水が過冷却器①で昇温された後，フラッシュタンクに供給される．また，このシステムでは蒸気を生成しながら同時に過冷却器②でプロセス加熱等に利用可能な温水も生成可能となっている．この過冷却器②へ供給される補給水温度および流量を調整することにより，生成する温水の温度および供給量を設定できる．

図 1 に蒸気生成システム概要を示す．

図 2 にユニット外観写真を示す．


Fig.2　Unit Exterior Appearance

(2) システム仕様

冷媒は環境影響が小さく安全性の高い HFO1336mzz(Z)を採用した．圧縮機は当社標準スクリュー圧縮機をベースとして，当該冷媒を使用した蒸気生成ヒートポンプで要求される高温条件に特殊仕様で対応した．

設計条件としては，凝縮温度 150℃，蒸発温度 75℃で 140℃の蒸気を 300kg/h 供給し，その際の目標 COP が 3.0 である．これらの仕様を満足するように圧縮機機種を選定し，蒸発器，凝縮器，過冷却器，液ガス熱交換器およびフラッシュタンクを設計した．

表 1 にヒートポンプ仕様を示す．

Table 1　Heat Pump Specifications

Item		Conditions/Specifications
Type		Water source steam generation heat pump
Refrigerant		HFO1336mzz(Z)
Comp.	Type	Oil-injected screw
	Specification	Max. discharge temp.180℃
Steam generation		Flush tank method
Design conditions	Cond. Temp.	150℃
	Eva. Temp.	75℃
	Heat capacity	200～300kW
	Steam temp.	140℃
	Steam flow rate	300～350kg/h
	Target COP	3.0

３．試験方法

蒸気生成ヒートポンプの性能を確認するため，熱源水系統，蒸気系統，温水系統の各温度，流量などを調整可能な試験設備を製作し，性能試験を実施した．

表 2 に試験を実施した際の温度条件を示す．

Table 2　Test Temperature Conditions

Item	Conditions
Condensation temperature	115～150℃
Evaporation temperature	50～75℃
Suction superheat temperature	17～42℃
Heat source water temperature	60～90℃
Steam temperature	110～140℃

ヒートポンプ冷媒系統，蒸気系統の能力は，各構成機器の出入口に設置した圧力センサー，温度センサーの測定値からエンタルピー差Δh【kJ/kg】，および流量計により測定した循環量【kg/s】を用いて算出した．熱源水系統，温水系統の能力は，熱交換器出入口の温度センサーの測定値，比熱【kJ/kg・K】，および流量計により測定した循環量【kg/s】を用いて算出した．また，電力【kW】は電力計により測定した．

４．試験結果

（1）設計条件試験結果

図 3 に設計条件における試験結果を示す．熱源水入口温度 86℃，熱源水出口温度 79℃，過冷却器①および過冷却器②の補給水入口温度 81℃の条件で運転したとき，フラッシュタンクで 140℃の蒸気を 330kg/h，過冷却器②で 92℃の温水を 6.4t/h 供給できた．このとき，凝縮器，過冷却器①，過冷却器②の加熱量を合算した総加熱能力は 317kW，電力は 107kW であり，加熱 COP は 3.0 であった． この結果，本システムで 140℃蒸気の安定供給が可能であることが確認できた．

図 3 に示すシステムでは，蒸気と温水を同時に生成可能であるが，温水を必要としない場合も考えられる．図 4 に過冷却器②を使用しない場合の試験結果を示す．

熱源水入口温度 85℃，熱源水出口温度 80℃，過冷却器①の補給水入口温度 80℃の条件で運転したとき，フラッシュタンクで 140℃の蒸気を 362kg/h 供給できた．総加熱能力および加熱 COP は小さくなるが，蒸気のみ必要なシステムでも安定した運転が可能であることが確認できた．

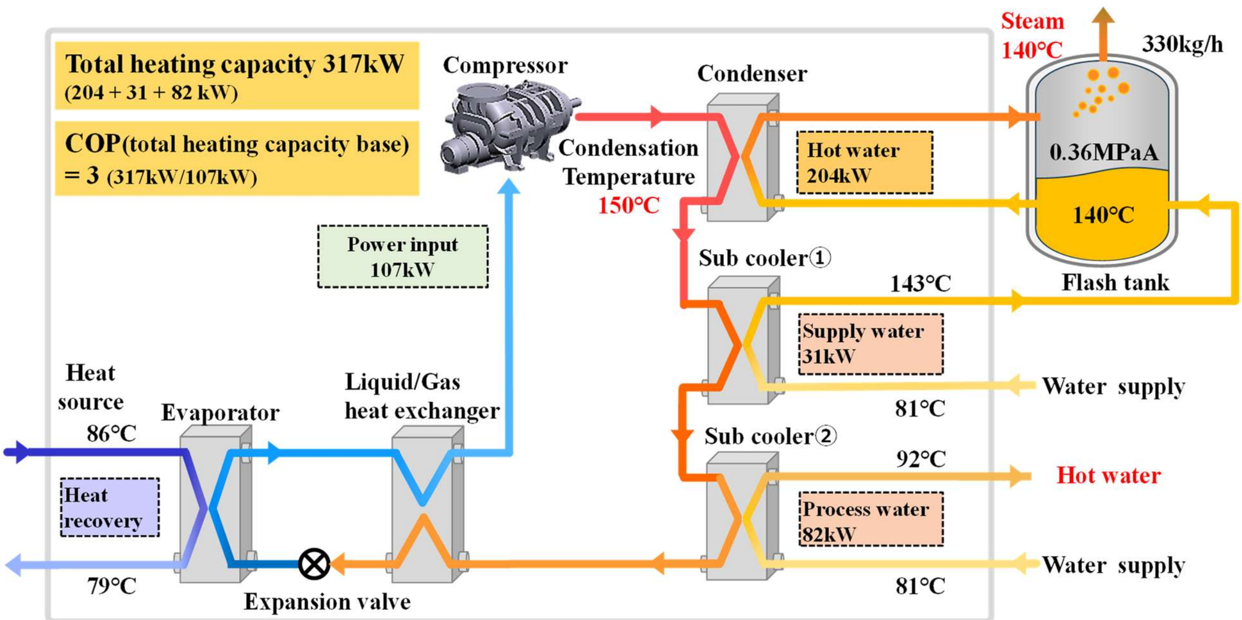

Fig.3　Test results under design conditions

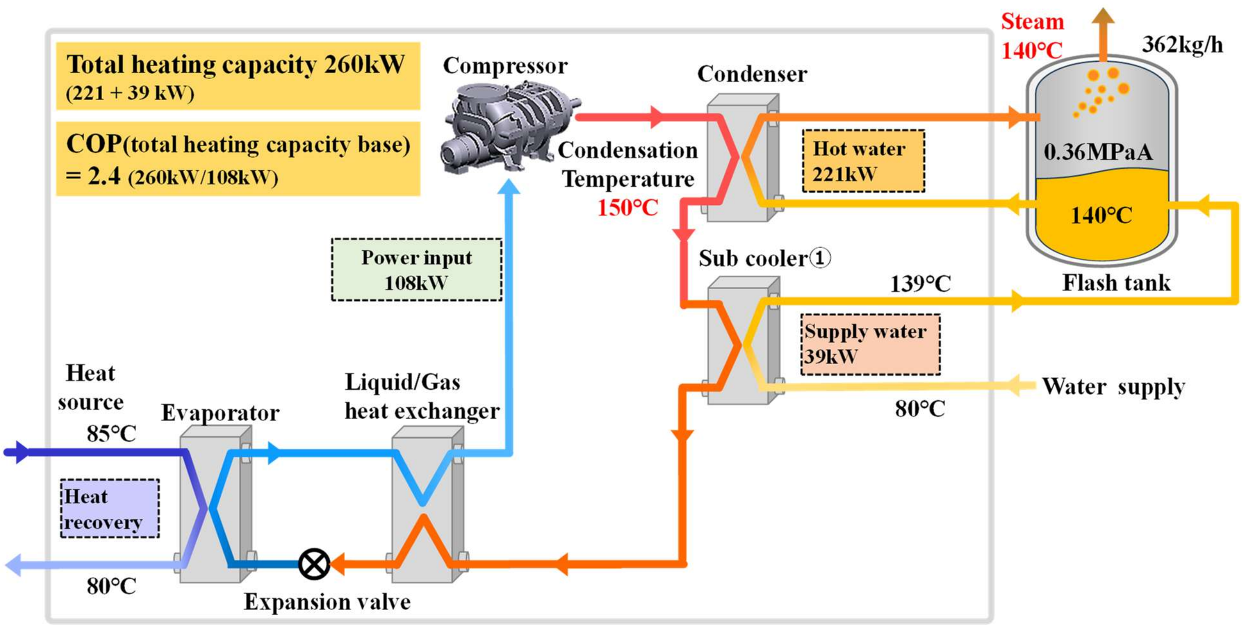

Fig.4　Test results under design conditions（Sub cooler (2) not used）

(2) 温度条件可変試験結果

蒸発温度および圧縮機吸入過熱度を変化させた際の加熱能力，蒸気供給量の変化を確認する試験を実施した．

図５に蒸発温度可変試験結果，図６に吸入過熱度可変試験結果を示す．

蒸発温度可変試験では，140℃の蒸気を供給する条件において，蒸発温度を 51～78℃と変化させたとき，加熱能力は 110～216kW，蒸気供給量は 179～358kg/h となった．51～78℃まで３～5℃刻みで蒸発温度を上昇させたとき，加熱能力および蒸気供給量は 10～15%ずつ大きくなった．この結果，蒸発温度 78℃の加熱能力と蒸気供給量は 51℃の値と比較して約２倍であった．

圧縮機吸入過熱度可変試験では，140℃の蒸気を供給する条件において，吸入過熱度を 17～42℃と変化させたとき，加熱能力は 191～221kW，蒸気供給量は 310～362kg/h となった．17～42℃まで３～5℃刻みで吸入過熱度を大きくしていったとき，加熱能力および蒸気供給量は 2～5%ずつ大きくなった．

図５および図６から，蒸発温度が高いほど，および圧縮機吸入過熱度が大きいほど，加熱能力および蒸気供給量が大きくなることが確認できた．これらのことから，運転条件の最適化によって性能向上が可能であることが確認できた．

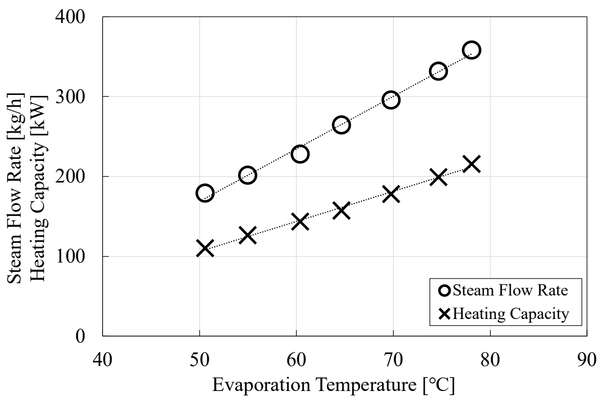

Fig.5　Evaporation temperature variable test result

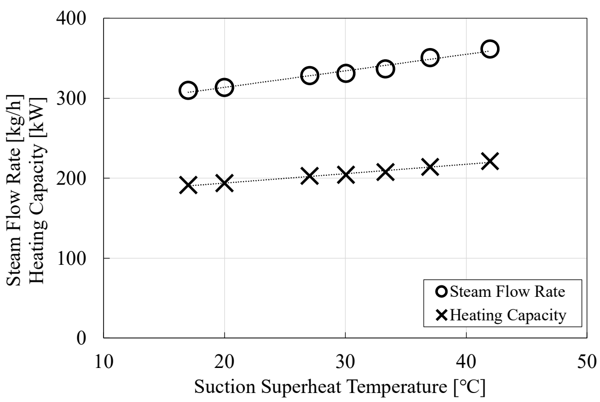

Fig.6　Suction superheat temperature variable test results

5. まとめ

本研究では低 GWP 冷媒 HFO1336mzz(Z)を用いた産業用蒸気生成ヒートポンプを開発し,140℃の高温蒸気を安定的に供給可能であることを確認した.設計条件下での試験において,加熱 COP3.0 を達成し,同時にプロセス加熱用の温水も生成可能であることを実証した.また,蒸発温度および圧縮機吸入過熱度の変化に伴う加熱能力および蒸気供給量の変化を評価し,運転条件の最適化によって性能向上が可能であることを示した.

本システムは,従来の化石燃料による蒸気供給に代わる環境負荷の少ない加熱技術として,産業分野の脱炭素化・電化・省エネルギーに大きく貢献するものであり,今後の普及が期待される.

この成果は、NEDO（国立研究開発法人新エネルギー・産業技術総合開発機構）の 助成事業（JPNP21005）の結果得られたものです。