Development of a Design Program for Industrrial Heat Pumps Based on a 1D Approach and a Commercial Component Specification Database

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Abstract

This study presents a one-dimensional design program for industrial heat pumps that integrates thermodynamic cycle calculations with a database of commercial compressors and expansion valves. The platform incorporates design algorithms for basic, IHX, vapor-injection, and newly added cascade cycles, and recommends suitable components by evaluating deviations between cycle requirements and equipment specifications. To validate the program, an R134a screw chiller was constructed using the recommended components, and its performance was compared with model predictions. The measured efficiency was 0.688 kW/usRT, showing a deviation of only 1.3% from the predicted 0.679 kW/usRT. The results confirm the accuracy and applicability of the proposed design tool for industrial heat-pump development.

Keywords: Industrial heat pumps; Design algorithm

1. Introduction

According to the IEA's sectoral data on global energy-related CO_2 emissions [1], the industrial sector accounts for approximately 23% of total global emissions. In 2021, it represented 38% (169 EJ) of global final energy consumption, and about 68% of this energy was still derived from fossil fuels [2]. To achieve significant emission reductions, fossil-fuel-based thermal systems such as boilers must be replaced with electrified alternatives. The Net Zero Roadmap [3] indicates that the share of electricity in light-industry energy consumption should reach 76% by 2050 to meet net-zero targets.

Heat pumps are a promising technology for industrial electrification because they can deliver several times more process heat per unit of electrical input compared to electric resistance heaters. Numerous studies have reported that replacing fossil-fuel-based process heat below 200 °C—widely required across industrial sectors—with heat pumps can reduce energy consumption by 40–60% [4–8]. Despite these advantages, comprehensive design methods for industrial heat-pump systems remain limited due to the large number of design variables involved, such as cycle configurations, component specifications, refrigerant selection, and degrees of superheating or subcooling [9]. As a result, small- and medium-sized enterprises (SMEs) often struggle to design optimized heat-pump systems because of their limited R&D capabilities and financial constraints in adopting advanced commercial tools. Effective dissemination of state-of-the-art national R&D technologies is therefore essential.

To support this need, previous work established design algorithms for three representative heat-pump cycle layouts—basic, internal-heat-exchanger (IHX), and vapor-injection cycles—within a thermal-energy design platform [10]. Building upon this foundation, the present study extends the platform by incorporating a cascade-cycle design module and developing a database that recommends appropriate compressor and expander models derived from calculated cycle performance. To validate the proposed enhancements, a heat-pump system was constructed using the recommended components, and its experimentally measured performance was compared with the corresponding cycle-calculation results to evaluate the accuracy of the design tool.

2. Heat pump design program

2.1. Input parameters for various heat pump designs

Table 1 presents the input parameters required for the various heat pump layouts. While the cold and hot process streams must be defined commonly across all layouts, each configuration requires its own set of additional inputs. In the case of the cascade cycle, the top and bottom cycles can be selected independently.

Table 1. Input list for heat pump design

Category	Input parameters	Symbol
Inputs of hot process (condenser)		
	Mass flow rate	$\dot{m}_h$
	Pressure	P_h
	Inlet temperature	T_{hi}
	Outlet temperature	T_{ho}
Inputs of cold process (evaporator)		
	Mass flow rate	$\dot{m}_c$
	Pressure	P_c
	Inlet temperature	T_{ci}
	Outlet temperature	T_{co}
Inputs of major components		
Basic cycle input *Commonly used in other layouts	Approach temperature (Plate type HX)	ΔT_{pp}
	LMTD (Fin type HX)	ΔT_{lmtd}
	Pressure drop in HX channels	ΔP
	Degree of superheat	ΔT_{sh}
	Degree of subcooling	ΔT_{sc}
	Isentropic efficiency of compressor	η_{comp}
IHX cycle input	Internal HX effectiveness	ε_{IHX}
Injection cycle	Isentropic efficiency of 2nd compressor	$\eta_{comp,2}$
Cascade cycle	Top cycle layout and inputs (Basic, IHX, Injection)	
	Bottom cycle layout and inputs (Basic, IHX, Injection)	

2.2. Flowcharts of heat pump design for each layout

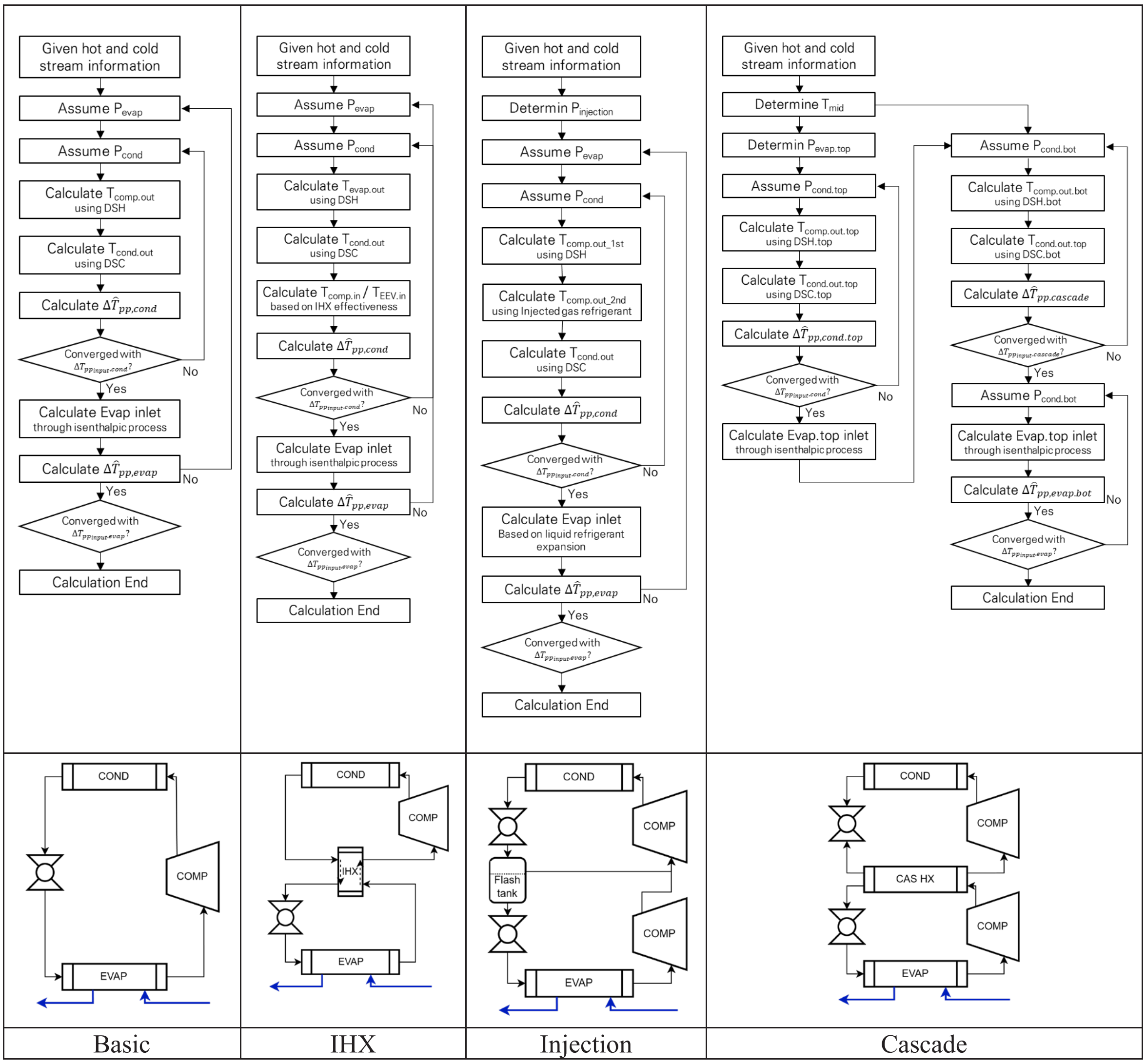


Figure 1. Flowcharts for heat pump design and schematics of each layout

Figure 1 presents the flowcharts for heat-pump design and the schematics of each layout. The condenser and evaporator pressures are first determined based on the given hot and cold process streams. Using the specified degree of superheat (DSH), the compressor inlet temperature is calculated, after which the compressor outlet temperature (i.e., condenser inlet temperature) is obtained using the compressor efficiency. The given degree of subcooling (DSC) is then applied to determine the condenser outlet temperature. Once the inlet and outlet states of the condenser are fully defined, the temperature profile between the refrigerant and the hot stream is evaluated by assuming uniform heat distribution, and the pinch temperature difference (ΔT_{pp}) is computed. The condenser pressure is subsequently adjusted until the calculated pinch point matches the specified value. The outlet state of the expansion valve is determined through an isenthalpic process. Finally, based on the evaporator inlet and outlet states, the evaporator pressure is also adjusted to meet the required evaporator pinch temperature.

2.3. Database of commercial compressors and expansion valves

Even though the thermodynamic states at each point of the heat-pump cycle can be calculated, selecting an appropriate compressor and expansion valve remains challenging. To address this, the program includes a database of commercial compressor and expansion-valve lineups from major manufacturers such as Danfoss, Bitzer, and Copeland, comprising a total of 3,192 models. To select the most suitable models based on the cycle calculation results, the selection algorithms for the EEV and the compressor are presented in Figures 2 and 3.

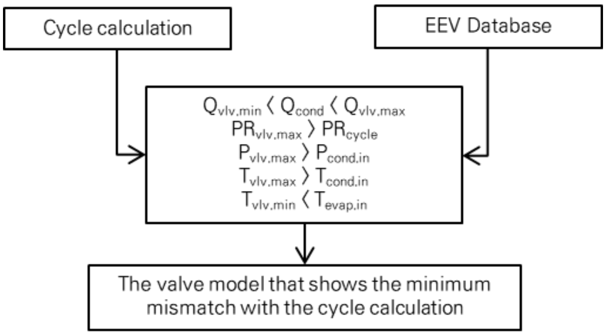
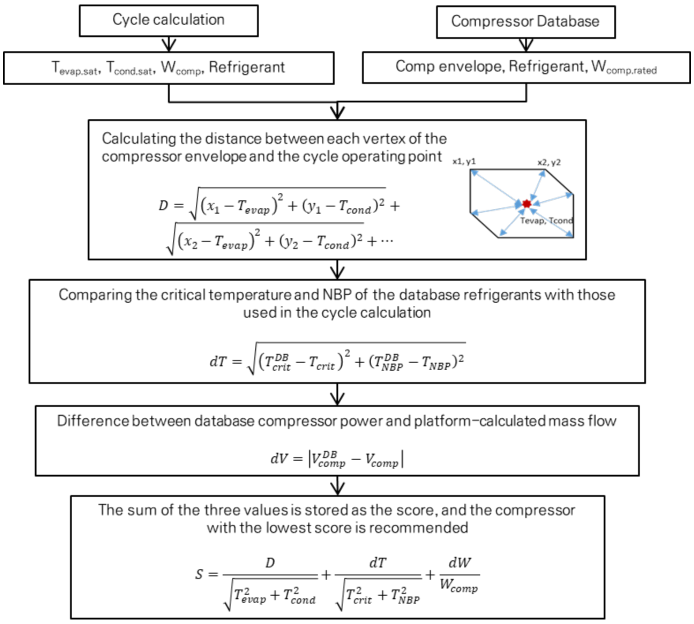


Figure 2. Selection algorithm of expansion valve



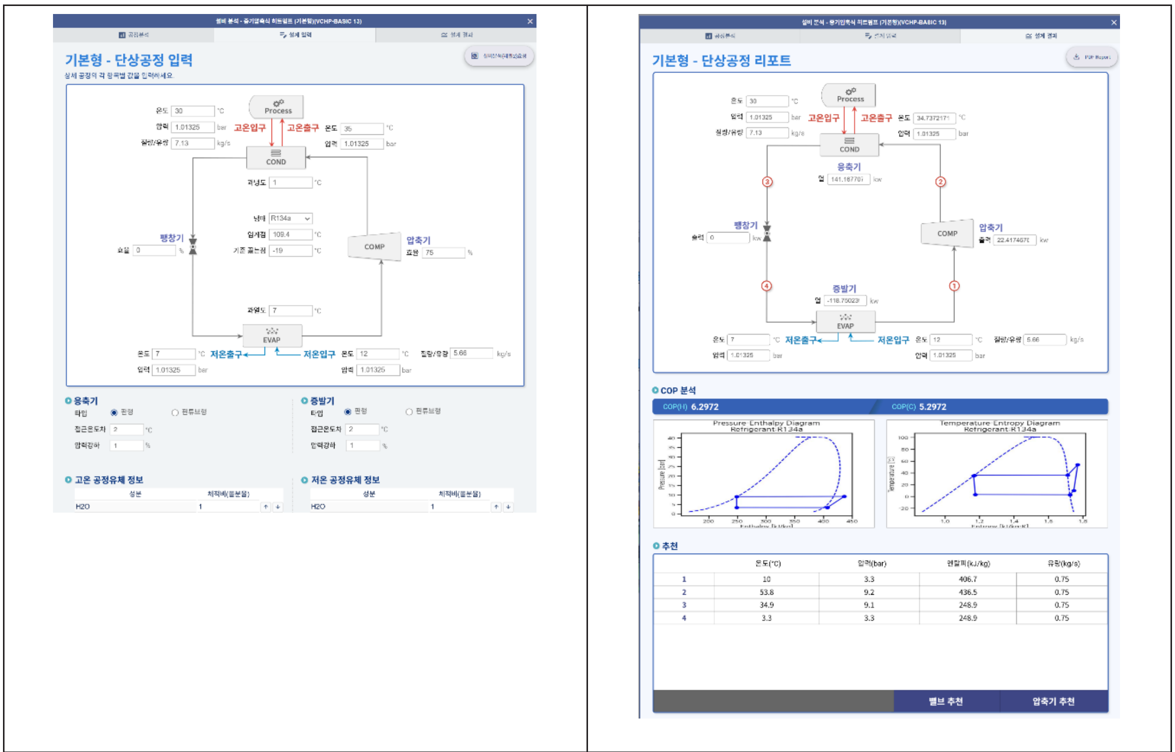
*NBP: Normal Boiling Point

Figure 3. Selection algorithm of compressor

3. Validation of Heat Pump Design Results

3.1. Cycle calculation

To validate the design results of the program, an actual heat pump system was constructed based on the selected components. An R134a screw chiller was chosen as the target device. The cold-stream inlet and outlet temperatures were 12 °C and 7 °C, respectively, while the hot-stream inlet temperature was 30 °C. The target cooling capacity of the system was approximately 120 kW. For the calculation, the compressor efficiency was assumed to be 75%. With these user inputs, the COP was predicted to be 5.3 which is equivalent to 0.68 kW/usRT, which is the ratio of power expressed in kilowatts (kW) to refrigeration capacity expressed in U.S. Refrigeration Tons (USRT). The reason why kW/usRT is used is that it normalizes power input (kW) by a standard measure of cooling output (USRT), allowing comparison of energy input relative to cooling performance. This can be helpful when evaluating energy efficiency or specific power consumption across systems with different sizes or rated cooling capacities. The program input interface and the corresponding cycle-calculation results are shown in Figure 4.

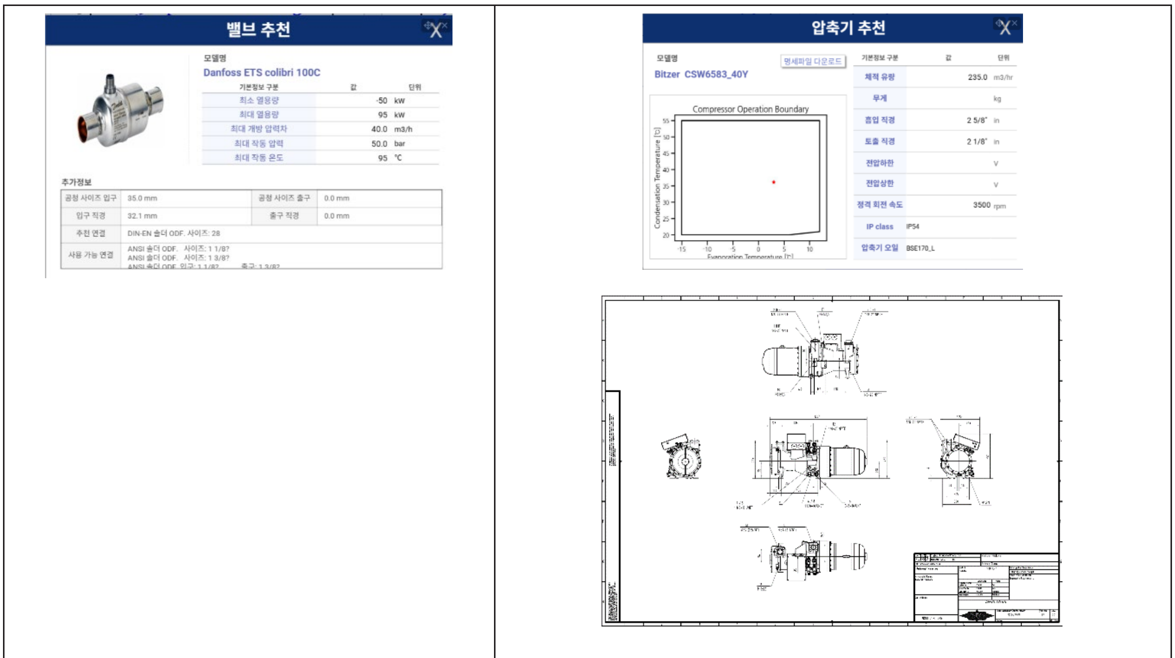


Heat pump cycle design inputs	Heat pump cycle design results

Figure 4. Heat pump cycle design using program

3.2. Component selection

From the cycle-calculation results, the recommended EEV was the Danfoss ETS 100C, and the recommended compressor was the Bitzer CSW6583-40Y, whose specifications are shown in Figure 5. Based on the cycle calculation results and the selected components, P&ID of the screw chiller was drawn as illustrated in Figure 6. Using these selected components, the heat pump system was constructed as presented in Figure 7.



EEV selection results	Compressor selection results

Figure 5. Component selection from the program

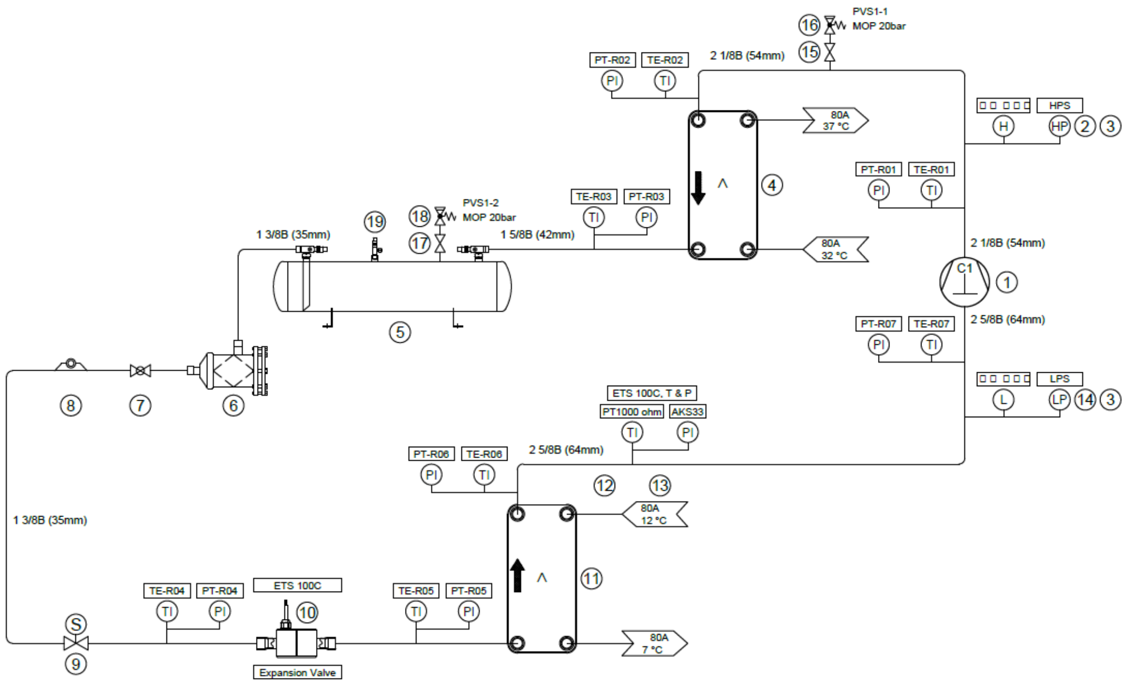


Figure 6. P&ID of the screw-chiller based on the program design result

Figure 7. The constructed screw chiller

3.3. Comparison to existing calculation tool

To verify the reliability of the program, its results were compared with those obtained from an existing calculation tool. CoolTools developed by DTU, which is a widely used design program for heat pumps, was selected as the reference. Using the same design parameters for an R134a chiller, CoolTools predicted a COP of 5.3057, while the program yielded a COP of 5.2972.

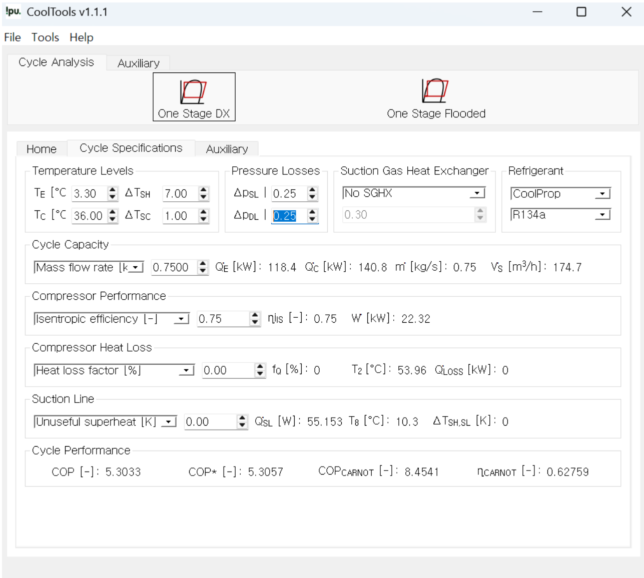
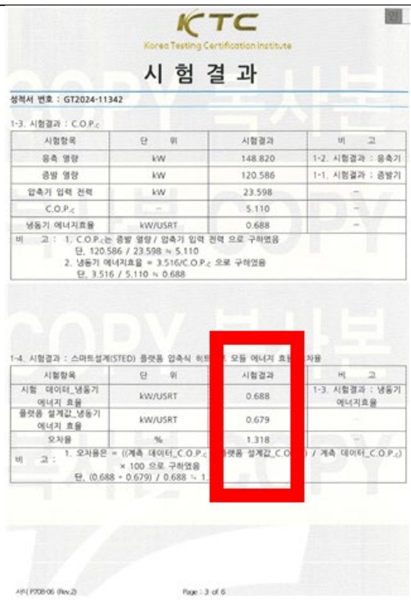


Figure 7. Calculation results of CoolTools

4. Results

To obtain official certification for the performance efficiency (kW/usRT) and the accuracy (error %) between the model predictions and experimental results of the high-efficiency screw chiller designed using the vapor-compression heat pump design module, the system was submitted to the Korea Testing Certification Institute (KTC) for accredited testing. The evaluation of the efficiency metrics and model accuracy was conducted under the conditions summarized in the table below, and the average values measured over a 60-minute period were used as the assessment indicators. The efficiency of the high-efficiency screw chiller designed using the platform was 0.679 kW/usRT, while the certified test result for the chiller constructed with the components designed and recommended by the platform was 0.688 kW/usRT. The difference between the model prediction and the certified test result corresponds to an error of 1.3%, confirming that the system meets the required quantitative performance criteria.

Program Prediction	Measurements
0.679 kW/usRT	0.688 kW/usRT
Deviation: 1.3%	



KTC
Korea Testing Certification Institute

시 험 결 과

성적서 번호 : GT2024-11342

1-3. 시험결과 : C.O.P.c

시험항목	단 위	시험결과	비 고
응축 열량	kW	148.820	1-2. 시험결과 : 응축기
증발 열량	kW	120.586	1-1. 시험결과 : 증발기
압축기 입력 전력	kW	23.598	–
C.O.P.c	–	5.110	–
냉동기 에너지효율	kW/USRT	0.688	–

비 고 : 1. C.O.P.c는 증발 열량 / 압축기 입력 전력 으로 구하였음
단, 120.586 / 23.598 ≒ 5.110
2. 냉동기 에너지효율 = 3.516/C.O.P.c 으로 구하였음
단, 3.516 / 5.110 ≒ 0.688

1-4. 시험결과 : 스마트설계(STED) 플랫폼 압축식 히트 [illegible] 모듈 에너지 효[illegible] 차율

시험항목	단 위	시험결과	비 고
시험 데이터_냉동기 에너지 효율	kW/USRT	0.688	1-3. 시험결과 : 냉동기 에너지효율
플랫폼 설계값_냉동기 에너지 효율	kW/USRT	0.679	–
오차율	%	1.318	–

비 고 : 1. 오차율은 = ((계측 데이터_C.O.P.c [illegible] 플랫폼 설계값_C.O[illegible]) / 계측 데이터_C.O.P.c)
× 100 으로 구하였음
단, (0.688 - 0.679) / 0.688 ≒ 1.[illegible]

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Figure 8. Certification of model deviation between the program predictions and experimental measurements

5. Conclusions

This study developed a one-dimensional design program for industrial heat pumps that integrates thermodynamic cycle calculations with a commercial component database and supports multiple cycle configurations, including basic, IHX, vapor-injection, and cascade cycles. The reliability of the program was first verified through comparison with CoolTools developed by DTU, a widely used heat-pump design software, showing close agreement in COP prediction for an R134a chiller under identical design conditions. Furthermore, the program's validity was experimentally confirmed by designing and testing an R134a screw chiller using the recommended components, where the measured efficiency of 0.688 kW/usRT differed by only 1.3% from the predicted 0.679 kW/usRT. These results demonstrate that the proposed design tool provides an accurate and practical platform for industrial heat-pump design and performance evaluation.

Acknowledgements

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