Scroll Compressor Development for Air-Source Heat Pump Water Heater Applications

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ABSTRACT

Different from normal refrigeration and air-conditioning systems, air-source heat pump water heater (HPWH) is a special refrigeration system involving higher condensing temperatures and a wide range of evaporating temperatures. The capability to reliably operate under high compression ratio, high discharge temperature, and high load has been the main challenge for the compressor design.

The scroll compressor has been proved for its superior reliability in both refrigeration and air conditioning applications. This paper presents the advantages of the scroll compressor in heat pump water heater applications. Enhanced Vapor Injection (EVI) technology improves the system performance across the entire operating envelope and the compressor reliability at low ambient temperatures. The major contributions from the EVI technology are discussed in details.

A prototype system with a flash tank as the economizer has been tested at various conditions. The performance optimization of the flash tank in the heat pump water heater system is discussed and the system testing data is presented.

1. INTRODUCTION

With global economy soaring and people's demand increasing on hot water supply in both household and commercial marketing, the energy consumption on water heating has been steadily growing up which brings not only much more costs but also serious environmental concerns if the heat is not provided in an efficient way. It is very important and urgent to find a heating solution that satisfies all the needs while reducing the adverse effects. Alternative heating solutions have been studied, and one of these is heat pump cycle. A heat pump is a device used for space heating in the current market, and it consists of the same hardware but operates at a reversed cycle of an air-conditioning device. For water heating, the situation for compressor and system design, considering its condensing temperatures, is a little different from space heating. This paper mainly discusses the compressor development for an air-source HPWH system. Suggestions on system design have also been summarized.

2. COMPRESSOR DEVELOPMENT

An HPWH is designed to supply hot water at an almost constant high temperature season by season. For the compressor, it needs to deliver a constant heating capacity when running at a high condensing temperature and various evaporating temperatures. The application range has to be extended to lower evaporating temperature (ET) and higher condensing temperature (CT) for the compressor, see Figure 1, and the highest compression ratio could be as 2 times high as it is in air-conditioning condition for R22 applications. This fundamental change will directly lead to extremely higher discharge temperature and pressure difference, heavier wear on components and more internal leakage between the sealing surfaces. This situation could also be a big challenge to motor due to lower

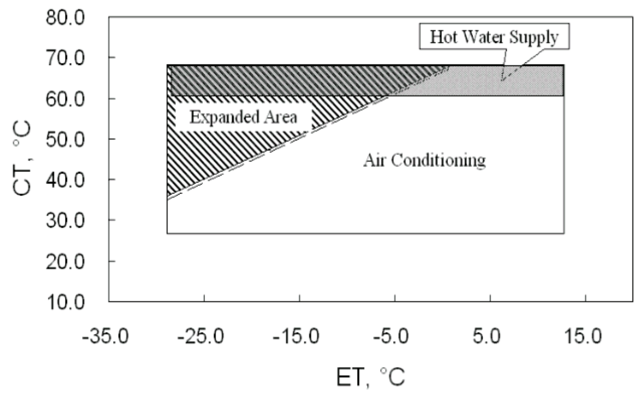


Figure 1: Application difference for air-conditioning and water heater compressor

efficiency and poor cooling. All these may result in efficiency decrease, motor overheating or compressor damage. All of these aspects should be paid attention to by the HPWH compressor designers.

Generally speaking, due to the rigorousness of water heater applications and the limited design margin of the current compressor under a competitive market, it is impossible to simply introduce an air-conditioning compressor to water heater application without any major technology improvements, although some A/C compressors have been applied in the HPWH systems with significantly reduced working life or limited operating scope.

Scroll compressors have been widely used in the current vapor compression refrigeration cycles in both commercial and household markets. In the past 20 years, scroll compressors have gained a good reputation with its excellent reliability and good efficiency. Scroll compressors have also expanded its temperature range under the help of liquid injection in some low temperature applications and enlarged its heating capacity by vapor injection in some heat pump applications. All of these made the possibility of introducing scroll compressor to the HPWH application in an efficient and economical way.

A complete study has been done to design and qualify a scroll compressor for the HPWH applications. Table 1 summarizes the scope of the study.

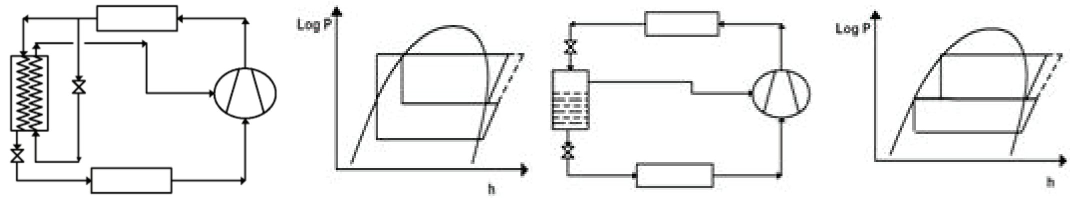
Table 1: HPWH compressor specification

Refrigerant	Oil	Ambient Temperature	End Water Temperature	Discharge Temperature	Life Expectancy
R-22	Mineral Oil	-30°C ~12°C	55°C ~60°C	=115°C	15 years

2.1 Enhanced vapor injection (EVI)

Generally, there are two technical obstacles that prevent the normal air-conditioning compressors from running at low ET and high CT. One is the low heating capacity delivery, and the other is the high discharge temperature and the effects it causes. EVI could be a good solution to both of the issues.

Vapor injection is similar to a two-stage cycle but with the inter-stage vapor injected into the same compressor. There are two approaches to produce the vapor source, one is a plate heat exchanger (PHX) and the other is a flash tank. Figure 2 shows system sketches and their *p-h* maps. For the PHX system, injection line refrigerant expands through one throttle device and exchanges heat with the liquid line (main line) refrigerant, and it saturates in the out let of PHX (could be superheated) while the liquid line gets more subcooling. The injection line mass flow can be directly adjusted through the throttle device. For the flash tank system, refrigerant in the flash tank saturates under one inter-pressure (could not be superheated) and injects into the compressor while the rest of the liquid continues running in the main cycle. The injection mass flow can also be adjusted by modulating the inter-pressure. Under this way, cooling and heating capacity could be brought up dramatically, about 10~30% depending on the evaporating and condensing pressures. Besides, the saturated vapor or wet gas mixes with the refrigerant in the inter-compression cavity and cools the scroll elements. By modulating the injection line expansion device and changing



(a) (b)

Figure 2: EVI system and *p-h* map, (a) PHX system and (b) flash tank system

the mass flow, the temperature in the scroll could be properly reduced and changes the way of refrigerant compression. EVI cooling produces an efficient and operational method to manage the temperature during the process of gas compression and to keep all the components and oil from getting too hot. So, EVI can not only be a good booster to the heating capacity but also a perfect solution to prevent the scroll compressor from being damaged by overheating.

Several attentions should be paid to when an EVI compressor is developed for water heater usage. One of these is that the location of the injection hole. It is better to design injection holes close but not communicated to the suction side, which maximizes the injection mass and minimizes the back-flow into the flash tank. This is very important in the flash tank system when no check valve is used in the injection line. The other attention is that all the non-metallic material should be wet-refrigerant proof. Power input when the vapor injection is on can be about 10% higher than at a vapor injection off condition.

Most of the failures caused by high temperature are lubricant burn and carbonization. Scroll compression cavities are shaped by the scroll bases and coupled meshing vanes. Oil film should always be there to help seal neighboring pressure cavities and to lubricate the contact surfaces between the vane tip and the scroll base. Heavy wear and burn could happen if the oil film is destroyed or its physical properties degrade significantly. High temperature at the scroll's discharge port area has been detected and the detected high temperature could be more than 50°F higher than we usually see in the compressor discharge outlet. A new safety temperature baseline has to be established based on these data, and then the injected inter-pressured vapor could properly cool down the scroll to the safety level and prevent oil from damage due to overheating.

2.2 Scroll reed valve

As typical staged compressors, air conditioning scroll compressors can work efficiently without any reed-type valve on suction or discharge sides. However, as to water heater application, with the increasing of CT (condensing pressure) and decreasing of ET (evaporating pressure), the real compression ratio goes up quickly, heavy recompression occurs and causes much more power input. One reed valve is designed to relieve this situation. See Figure 3. The reed valve assembly includes one valve stop, one valve plate and the reed itself. It sits on the discharge port of upper scroll and firmly fixed by the retainer. It opens when the pressure reaches the condensing pressure. When the valve closes, it separates the scroll compression cavity and the discharge muffler and limits the recompression. This helps the compressor run in a more efficient way.

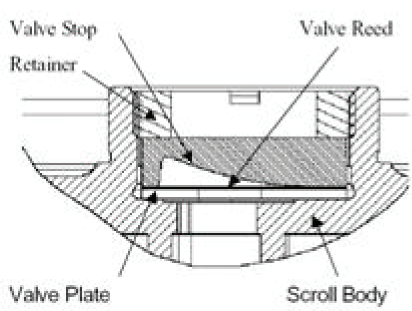


Figure 3: Valve assembly on upper scroll

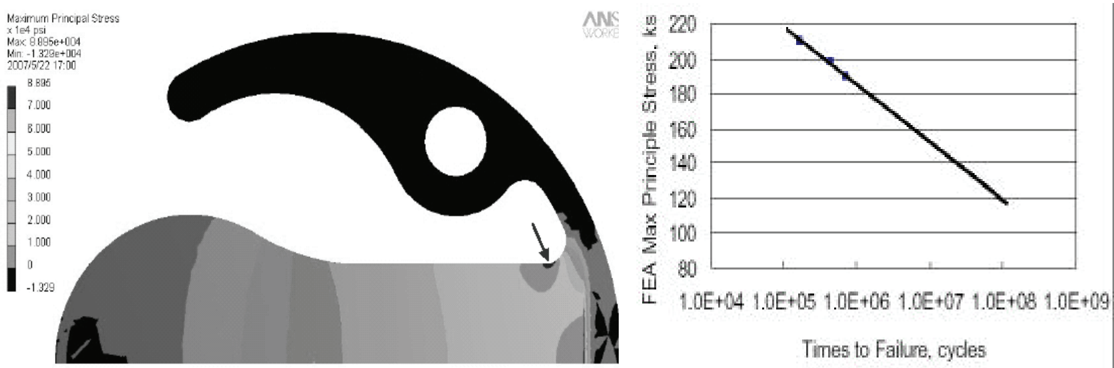
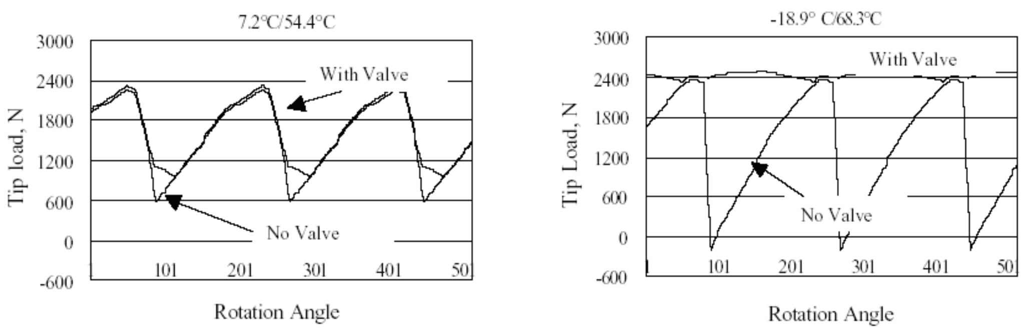


Figure 4: FEA simulation and fatigue life of valve reed (Valve steel of 0.010 inch thickness)



(a) Typical air-conditioning condition
7.2° C/54.4° C , Compression ratio=3.3

(b) High compression ratio condition of HPWH
-18.9°C/68.3°C, Compression ratio=16.9

Figure 5: Calculation of scroll tip force

Fatigue life of the valve reed had been evaluated and results showed that the reed has sufficient fatigue strength to withstand 10^9 cycles with a 99.9% probability of survival at maximum allowable deflection of the reed, see Figure 4.

Load forces on the coupled scroll vane tips change when the reed valve is applied since condensing pressure on the scroll will generally be in a same high level. Calculation had been done on both low compression ratio and high compression ratio, with or without reed valve. See the Figure 5 for loads at different orbiting angle. Generally, the load on scroll tips is cyclic downward and upward during a whole running cycle. When a reed valve is applied, the tip load changes differently depending on conditions, lightly at low compression ratio but significantly at high compression ratio. And, the load curve also shows that with the compression ratio goes up the load change on the scroll tip becomes smaller and finally reaches a relatively constant value. This change, on one hand, helps scroll run more evenly, on the other hand however, increases the average load of whole cycle.

From the curve of “No valve” in Figure 5 (a), 600 Newton contact force could be viewed as a minimum tip load to maintain enough tip sealing on air-conditioning, and the curve in Figure.5 (b) tells that the tip load is insufficient in about 15% duration, even comes to 0 at some moments if no reed valve is used.

The gain and loss under different conditions can also be seen in the perspective of the compressor running power. At ARI (7.2°C/54.4° C), the reed valve may cause about 2~4% additional power input. While at the application of an HPWH, at high percentage of the time, the compressor operates with high compression ratio, then the raised load can reduce inner leakage and prevent unloading of scroll sets and guarantees the scroll’s running in a more efficient way.

3. AIR-SOURCE HPWH SYSTEM DEVELOPMENT

One prototyping air-source HPWH system is built for testing. Data were obtained under various conditions, including system efficiency at different ambient temperatures, efficiency with or without vapor injection, and with or without the scroll reed valve.

3.1 Air-source HPWH test hardware development

There are two types of air-source HPWH system designs in current market, one-time heating air-source HPWH system and circulating heating air-source HPWH system. This paper will only focus on circulating heating air-source HPWH system. See Figure 6 for a layout of air-source HPWH system test room. The temperature and humidity at the test points in the room is controlled based on China's Standard. Figure 7 shows the schematic of the circulating air-source HPWH system with a flash-tank. And it consists of tube-in-tube heat exchanger (condenser), a scroll compressor with vapor injection technology, an evaporator, a separator, a solenoid valve, a flash tank, a four-way valve and an EXV. The intermediate pressure and evaporating temperature can be adjusted by the EXV valve.

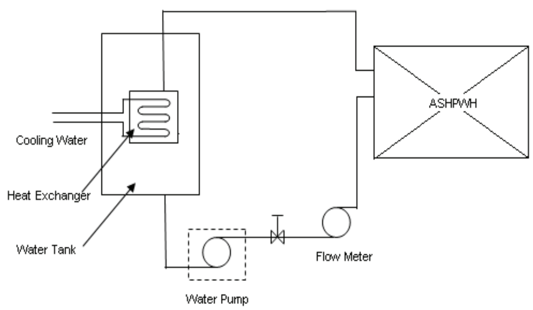


Figure 6: Layout of circulating air-source HPWH system test room

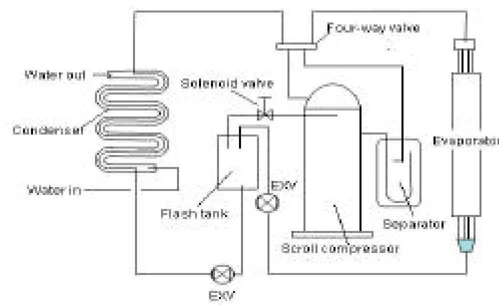


Figure 7: Schematic of circulating air-source HPWH unit with a flash tank

3.2 Test at standard rating condition

Table 2: Rating conditions of heat pump water heater in China standard

Application	Condition	Water Temperature, °C		Ambient Temperature, °C	
		Initial	Termination	DB	WB
Normal Temperature (0~43 ° C)	Rated Point	15	55	20	15
	High Load	29	55	43	26
	Light Load	9	55	7	6
	Defrost	9	55	2	1
Low Temperature (-10~38 ° C)	Rated Point	9	55	7	6
	High Load	29	55	38	23
	Light Load	9	55	-7	-8
	Defrost	9	55	2	1

Table 3: Minimum COP of air-source heat pump water heater in China standard

Type		Normal W/W	Low Temp W/W
One-time heating HPWH		3.7	3.1
Circulating heating HPWH	Not Including Water Pump Power	3.7	3.1
	Including Water Pump Power	3.6	3

With the continuous development of the economy in China, the government is paying more and more attention on environmental protection and energy saving. China's new standard about the air-source HPWH system, heat pump water heater for commercial and industrial and similar applications, will be implemented on May.1, 2008. This standard will be used as our guidelines for air-source HPWH system testing. Table 2 shows the rating conditions about an air-source HPWH in the standard. Table 3 shows the performance efficiency of an air-source HPWH system that must be met in China.

3.3 Theoretical calculation model

When the water out temperature goes up, the condensing temperature in the condenser will also rise up and the average capacity and power are calculated by the following method.

The air-source HPWH system's average capacity is calculated by

$$Q_h = C_w \times G_w \times (t_2 - t_1)/(3600 \times H \times 1000) + Q_x + Q_l \qquad (1)$$

With $$Q_x = \sum_{i=0}^{i=n} C_i G_i \times (t_2 - t_1) \qquad (2)$$

With $$Q_l = \frac{\dfrac{C_W \cdot G_W \cdot DT}{DH}}{(t_2 - t_a)} \times \left\{ \left[t_1 + \frac{(t_2 - t_1)}{2} \right] - t_a \right\} \qquad (3)$$

The air-source HPWH system's average power consumption is

$$E = N / H \qquad (4)$$

The air-source HPWH system's coefficient of performance is

$$COP = Q_h / E \qquad (5)$$

3.4 Analysis of experimental results

The entire manuscript (i.e., text, figures, tables, bibliography, etc.) must be no more than eight (8) pages long including graphs, tables and pictures. Any manuscript having excess pages will not be published.

3.4.1 Efficiency test with and without vapor injection

The air-source HPWH with vapor injection can get better efficiency than without vapor injection at low ambient temperature, see the data shown in Figure 8. This test is based on 65℃ water terminal temperature and -10℃ ambient temperature. The heating time drops from 6.3 hours to 4.3 hours. The heating COP has a 20% improvement compared to without vapor injection.

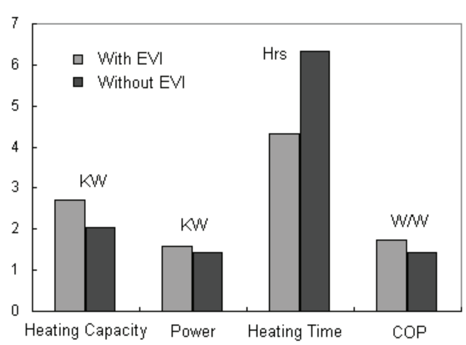


Figure 8: Efficiency test results with EVI and Without EVI

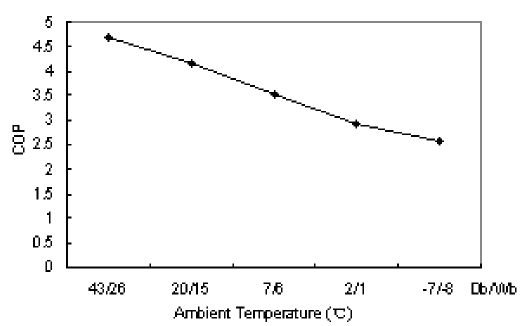


Figure 9: COP at different ambient temperature

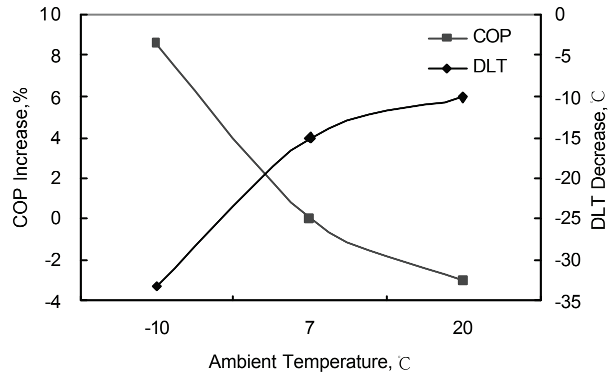


Figure 10: COP and DLT improvement with reed valve to without reed valve

3.4.2 COP of the air-source HPWH system with different ambient temperatures
Based on China standard, the water is heated from 15℃ to 55℃ in different ambient temperatures. Figure 9 shows the COP drops due to capacity decrease and power increase from high ambient temperature to low ambient temperature. The COP is 4.2 at 20℃ ambient and 3.6 at 7℃ ambient.

3.4.3 Efficiency test with and without scroll reed valve
The effects of the scroll reed valve have also been evaluated. The air-source HPWH system with and without a scroll reed valve is tested separately. See the Figure 10 for the comparison between these two cases at different ambient temperatures. At lower temperatures, COP increases and DLT decreases with a scroll reed valve installed.

4. CONCLUSIONS

A compressor has been developed for HPWH application. The effects of vapor injection and the scroll reed valve have been fully discussed on both compressor design and system test sides. The vapor injection made the most of contribution to heating capacity increase for water heating and overheating protection. A reed valve on the discharge side helps compressor run more efficiently and with lower DLT. All of these technologies are critical to the success of HPWH compressor development

NOMENCLATURE

Symbol	Description	Unit	Index	Description
Q	Heating capacity	[KW]	1	Initial water
C	Specific heat	[KJ/（kg·℃）]	2	Terminal water
G	Water Weight	[Kg]	w	Water
t	Water temperature	[℃]	x	Tank saving
H	Heating time	[hrs]	l	Tank leakage
E	Unit consumed power	[KW]	i	Tank and pipe etc
N	Total consumption energy	[KJ]	a	Ambient
COP	Coefficient of performance	[-]		
K	Heat transfer coefficient	[KW/(m2.k)]		
A	Tank area	M2		
DT	Leakage temperature difference	℃		
DH	Leakage time difference	℃		