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PERFORMANCE COMPARISON BETWEEN CONSTANT SPEED AND VARIABLE SPEED OF SCROLL COMPRESSORS USING R-410A

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ABSTRACT

Combined HFC-410A (R-410A) with DC brushless motor and inverter control technology to improve the performance of compressor has being used in the room air-conditioner gradually. The first objective in this study is to focus on the optimization of the new model of scroll-type compressor (STC) associated with the alternative refrigerants R-410A that is considered to be the major substitutes for HCFC-22 (R-22), and the result is that scroll set needs to be redesigned only from existing R-22 STC. Thereafter, to investigate the performance comparisons between constant speed with AC motor and variable speed with DC brushless motor of this STC prototype under specified operation conditions is the second objective. At 3470±1% rpm of motor rotation speed, the performance of the R-410A STC with DC brushless motor has higher than which is with AC motor about 2%~9%. But combined with sensorless driver operating efficiency for this R-410A STC with DC brushless motor, the performance has lower than which is with AC motor about 3%~10%.

NOMENCLATURE

C_{leak} : Leakage clearance between fixed scroll and orbiting scroll
D_o : Outside diameter of scroll set
D_{omax}: Maximum outside diameter of scroll set
D_{motor}: Maximum outside diameter of motor
E.E.R. Energy efficiency ratio of compressor
G_w: Rigidity of scroll wrap
h : Height of scroll wrap
N : Cyclic number of scroll wrap
p : Pitch of scroll wrap
p_b : Back-pressure applied in the back of fixed scroll
$P_{bearing}$: Bearing power loss of compressor
P_{comp} : Compression power loss of compressor
$P_{friction}$: Friction power loss of compressor
P_{motor} : Input power of the motor
P_{mech}: Mechanical power loss of compressor
$\dot{Q}_c$: Cooling capacity of compressor
r_{ob} : Orbiting radius of STC
t : Thickness of scroll wrap
V_s : Displacement volume of compressor
δ : Assembly space of compressor
ϕ_E : Extended angle of scroll wrap
η_{motor}: Motor efficiency
μ_i : Frictional coefficient of each contact surface inside of STC

INDRODUCTION

The Montreal Protoco will ban the use of HCFC-22 (R-22) by the year 2020 because it is an ozone-depleting substance. As for R-22 is the major refrigerant used in room and packaged air-conditioners, therefore, many extensive researches for potential replacements have been made during recent years. Currently, new refrigerants HFC-410A (R-410A) are considered to be the major substitutes for R-22. Note that the vapor pressure of R-410A is about 60% higher than that of R-22. As a result, in order to achieve competitive performance relative to R-22, the design modification to the existing compressor is needed. Among the known compressors, the scroll type compressor (STC) was known for its have high isentropic and volumetric efficiency, lower noise and more vibration free, has been becoming popular in the applications of room and packaged air-conditioners. Specially, the STC used in inverter-controlled applications have been popular gradually in Asia area. In this connection, it is important to investigate the characteristics of the STC subjected to alternative refrigerants and combined with inverter control technology. The objective of this study is to focus on the optimization of the STC associated with the alternative refrigerants R-410A and approach with the least change from existing compressor of R-22, in the mean time, to investigate the performance comparisons between the STC with AC motor and DC brushless motor.

OUTLINE OF THE DESIGN MODEL AND SPECIFICATIONS

Figure 1 shows the cross section of a hermetic STC used for room air-conditioners. The key components in this STC include a scroll set (fixed and orbiting scroll with involute scroll wraps), a set of solid axial compliance mechanism applied back-pressure in the back of fixed scroll, an Oldham coupling ring, three bearings (upper bearing, main bearing, lower bearing), an eccentric shaft and a driving motor. In this study, the examined structure of the STC is a low-pressure-shell design.

The original design data of STC used in R-22 refrigerant and with AC motor to operate at constant speed has shown as Table 1.

The requirements of new model design used for R-410A are given as Table 2. Table 3 shows the rated operation conditions to evaluate the basic performance of this study.

DESCRIPTION OF THE OPTIMIZATION DESIGN PROCESS

• Definition of the objective function

The objective function under evaluation in this study is the energy efficient ratio (E.E.R.), which is given as follows:

$$\text{E.E.R.} = \frac{\dot{Q}_c(\Delta T_{\sup}, C_{leak})}{P_{motor}(\eta_{motor})} = \frac{\dot{Q}_c(\Delta T_{\sup}, C_{leak})}{\left(\dfrac{P_{comp}(C_{leak}) + P_{fric}(p_b, \mu_i) + P_{bearing}(\Delta T_{\sup})}{\eta_{motor}}\right)},$$

where $\dot{Q}_c$ is the cooling capacity, which depends on the properties of refrigerant and is function of the displacement volume of compressor V_s.

The relationship between displacement volume V_s and major geometry parameters of scroll wrap are given by Morishita et al. (1984):

$$V_s = \pi p(p-2t)h(2N-1), \tag{2}$$

where p is pitch of scroll wrap, t is thickness of scroll wrap, h is height of scroll wrap, N is defined as equation (3).

$$N = \frac{\phi_E}{360} - \frac{1}{4}, \tag{3}$$

where ϕ_E is scroll extended angle. Four major design parameters are presented here: p, t, h and ϕ_E, these four relevant design variables are given in Figure 2.

By the way, the cooling capacity $\dot{Q}_c$ is related to the suction superheat $\Delta T_{\sup}$ and leakage clearance C_{leak} between fixed scroll and orbiting scroll (Yanagisawa, 1985).

P_{motor} is input power of motor:

$$P_{motor} = \frac{P_{mech}}{\eta_{motor}},$$

where η_{motor} is motor efficiency, P_{mech} is mechanical power loss that can be written as: (Puff et al., 1992)

$$P_{mech} = P_{comp} + P_{friction} + P_{bearing} \tag{5}$$

In Eq. (5), P_{comp} is the compression power loss that is related to C_{leak} (Rodgers et al., 1990 and Nieter et al., 1992). Frictional power loss $P_{friction}$ is related to back pressure p_b and friction coefficient of each contact surface μ_i .

$P_{bearing}$ is bearing power loss associated with each bearing in STC, which is a function of $\Delta T_{\sup}$. Detailed information on the bearing with respect to operating force within the STC can be found from Morishita et al. (1986), their corresponding correlation has been developed by Booker (1965, 1969, 1971) for oil viscosity vs. temperature was selected to use in this study.

- **Design constraints**

According to the finite element analysis and discuss with manufacturers to collect the constraints of scroll wrap, three critical design parameters are defined as below:

$$G_w = \frac{h}{t}, \tag{6}$$

$$D_o \le D_{o\max} = D_{motor} - \delta, \tag{7}$$

$$r_{ob} = \frac{p}{2} - t, \tag{8}$$

where G_w is rigidity of scroll wrap, D_o is the outside diameter of scroll set can be obtained from the largest coordinates of its scroll wrap, $D_{o\max}$ is the maximum outside diameter of STC, D_{motor} is the outside diameter of motor, and δ is assembly space, r_{ob} is orbiting radius of scroll set.

To meet the objective of least change for the R-410A STC model from existing R-22 STC, this study selects to use same eccentric shaft between these two STC models, it means the R-410A STC will design to use same value of orbiting radius r_{ob} as original STC of R-22. From this constraint, the four design variables p , t , h and ϕ_E can be reduced to three as t , h and ϕ_E .

The other constraint as Table 2 shows, the cooling capacity of this STC model will limit the allowable tolerance as 1% at rated operating condition.

Therefore, the total design constraints in this study are defined as Table 4.

- **Design process**

For the requirements of the smallest design change, modified the height of scroll wrap of R-22 STC only, should be the first approach in this investigation. Figure 3 shows the calculated result of this first design approach, but it cannot satisfy the required objective of E.E.R. at 2500kcal/h. Therefore, based on the same value of orbiting radius r_{ob} and then evaluated by an optimum design approach to achieve the objective of requirement for this R-410A STC is needed.

The optimum design process in this investigation has shown in Figure 6 and the analysis tool is one computer software package for STC design simulation, which is developed by ITRI.

A sequence of optimizing the STC subjected to change search direction of scroll extended angle match with height of scroll wrap. On the basis of one search direction, change the step size of thickness of scroll wrap and approach to optimize the scroll wrap geometry. Finally, propose an optimized design subject to practical design limits of the R-410A STC Model.

- **Design results**

Figure 4 shows the evaluated result from optimum design process, every scroll extended angle can be converged into one height value of scroll wrap at specified thickness under every constraints as Table 4 shows and meet the objective requirements of cooling capacity and E.E.R.

Due to this R-410A STC model will operate at lower compression ratios as Table 5 shows. Therefore, $\phi_E = 930^\circ, h = 13.1, t = 2.4$ is selected as final design, Table 6 shows the detailed design data. In practical application, three parts has been design change only from original R22 STC in this study. There are fixed scroll, orbiting scroll and the components of backpressure supplier mechanism.

EXPERIMENTAL RESULTS

The prototype of the new R-410A STC model has been assembly with AC motor and DC brushless motor, and tested at calorimeter of compressor respectively. Detailed results of the compressor performance are measured, which included cooling capacity, power consumption and energy efficiency ratio (E.E.R.). Table 5 has shown four specified operating conditions as A, B, C, D, to verify the performance of these two models of STC in this investigation.

Because the rotor of DC brushless motor has four pieces of permanent magnets insert into or surface mounted on the core of rotor and hermetic assembly inside the STC, it has to develop a sensorless driver to operate the STC, in the mean time, the sensorless driver has power loss when operate the STC. Therefore, the second stage is to investigate the performance comparisons between AC motor and DC brushless motor with sensorless driver .

Base on the performance of R-410A STC with AC motor and operate at 3470±1% rpm of motor speed, the cooling capacity under four specified conditions are 2581.6 kcal/h, 3079.0 kcal/h, 3304.0 kcal/h, 3510.0kcal/h, and the E.E.R. are 2.39 kcal/h/W, 3.14 kcal/h/W, 3.46 kcal/h/W and 3.86 kcal/h/W, respectively. Figure 5 shows the comparisons of cooling capacity, power consumption and E.E.R. between the R-410A STC model with AC motor, this model with DC brushless motor but not include driver power loss and the model with DC brushless motor include driver power loss.

The result for the E.E.R. of this R-410A STC with DC brushless motor has higher than which is with AC motor about 2%~9%. But combined with sensorless driver operating efficiency for this R-410A STC with DC brushless motor, the performance has lower than which is with AC motor about 3%~10%. Figure 5(a)~5(d) have shown the detail data.

CONCLUSIONS

This study demonstrated a practical process of design optimization of a STC for alternative refrigerants R-410A. The efficiency of R-410A can be reach to requirements after optimization. The prototype of new model has been verified in performance with AC motor and DC brushless motor at calorimeter. Some important results in this study are summarized as below:

(1) Except three parts need to design change only, the other components of the STC model used in R22 originally need not change and can be transferred to this R-410A STC model.

(2) Four major design variables p, t, h and ϕ_E are used in this study and has been reduced to three t, h and ϕ_E during optimization process, and the final optimization design is $\phi_E = 930^\circ, h = 13.1, t = 2.4$.

(3) After optimization, the E.E.R. of R-410A STC can be reached to 2.41kcal/h/W at rated operating condition and meet the objective requirement of this study. But in practice, the E.E.R. of prototype of the new model is 2.39kcal/h/W, have not met the performance requirement and need to investigate continuously.

(4) The sensorless driver technology has been developed for the R-410A STC with DC brushless motor.

(5) At 3470±1% rpm of one specified rotation speed of motor, the E.E.R. of this R-410A STC with DC brushless motor has higher than it with AC motor about 2%~9%. But include the sensorless driver power loss of this R-410A STC with DC brushless motor, the E.E.R. has lower than which is with AC motor about 3%~10%.

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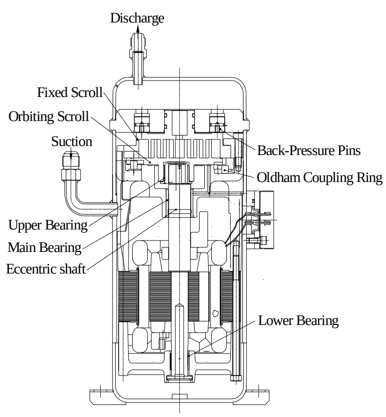


Figure 1: Scroll type compressor model

Table 1: Initial design of the R-22 STC used in this study

Refrigerant	R-22
Cooling Capacity (kcal/h)	2500
Height of Scroll Wrap (mm), h	14.5
Pitch of Scroll Wrap (mm), p	12.0
Thickness of Scroll Wrap (mm), t	3.0
Orbiting radius of STC (mm), r_{ob}	3.0
Extending angle of Scroll Wrap (mm), ϕ_E	1050.0
Outside diameter of scroll set (mm), D_o	73.0
AC motor Efficiency η_{motor}	84 %

Table 2: Requirements of the R-410A STC used in this study

Refrigerant	R-410A
Input Power	220V/1ϕ
Lubricants	POE VG32
Shell type	Low pressure shell
Motor outside diameter	110 mm
Motor type	2-Pole AC motor with constant speed & 4-Pole PM motor with DC brushless controlled
Cooling Capacity at rated operating condition	2500 kcal/h ±1%
Objective of E.E.R. at rated operating condition	≧ 2.40 kcal/h/W

Table 3: Rated operating conditions of this STC model

Condensing Temp.	Evaporating Temp.	Subcooling Temp.	Superheating Temp.	Room Temp.
54.4℃	7.2°C	8.3°C	27.8°C	35°C

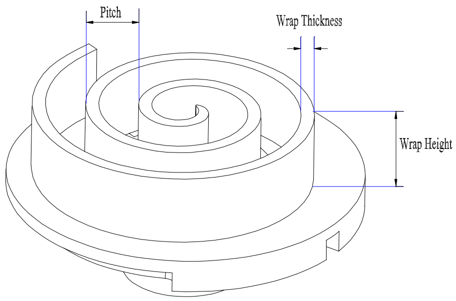


Figure 2: Major Design variables of the scroll wrap

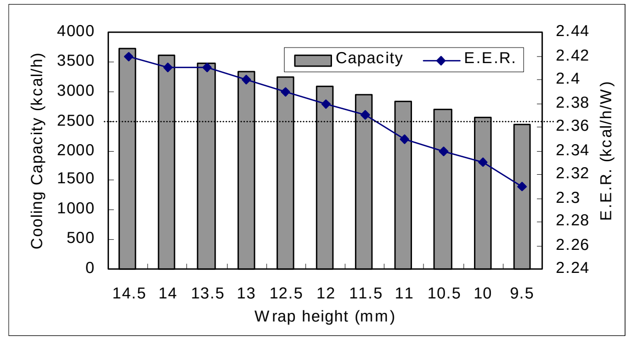


Figure 3: Data of first design approach in this study

Table 4: Design constraints in this study

Item No.	Design Constraints	Notes
1	$D_o \le D_{o\max} = 75mm$	$D_{motor} = 110mm$ 、 $\delta \approx 35mm$
2	$G_w \le 6.0$	Come from finite element analysis of stress deflection used in R-410 STC model and wrap machining capability
3	$r_{ob} = 3.0$	Come from original data of 2500kcal/h of STC of R-22
4	$2475kcal/h \le Q_c \le 2525kcal/h$	Depend on the specification of this study

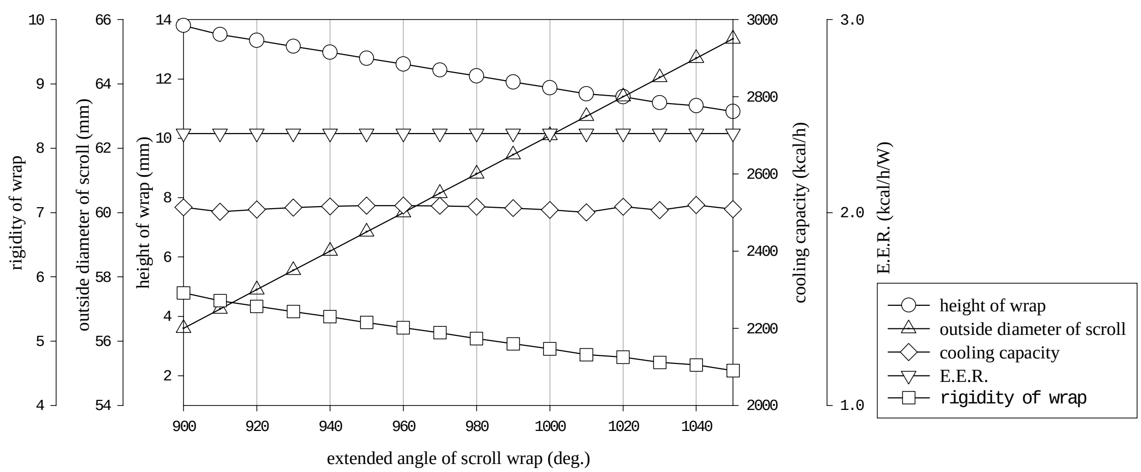


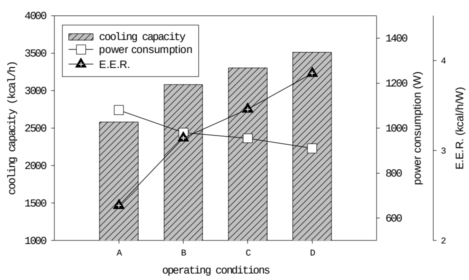
Figure 4: Evaluated result with optimum design process in this study

Table 5: The specified operation conditions for the R-410A STC

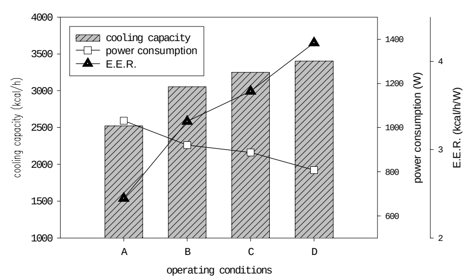
Operating Condition	Condensing Temp.	Evaporating Temp.	Sub-cooling Temp.	Superheating Temp.	Suction Temp.	Compression Ratio
A	54.4℃	7.3℃	8.3℃	27.7℃	35℃	3.38
B	50.0℃	11.0℃	8.3℃	24.0℃	35℃	2.74
C	50.0℃	13.5℃	8.3℃	21.5℃	35℃	2.55
D	47.0℃	14.5℃	8.3℃	20.5℃	35℃	2.31

Table 6: Data of final result

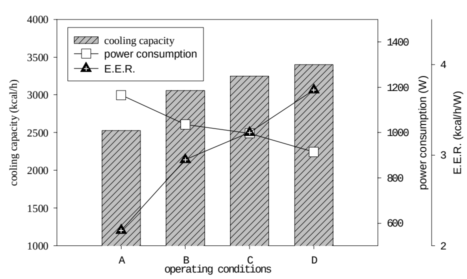
Refrigerant	R-410A
Height of Scroll Wrap (mm), h	13.1
Pitch of Scroll Wrap (mm), p	10.8
Thickness of Scroll Wrap (mm), t	2.4
Extending angle of Scroll Wrap (mm), ϕ_E	930
Rigidity of Scroll Wrap, G_w	5.46
Orbiting radius of STC (mm), r_{ob}	3.0
Outside diameter of scroll set (mm), D_o	58.2
Cooling Capacity at rated operating condition (kcal/h)	2512.7
E.E.R. (kcal/h/W)	2.41



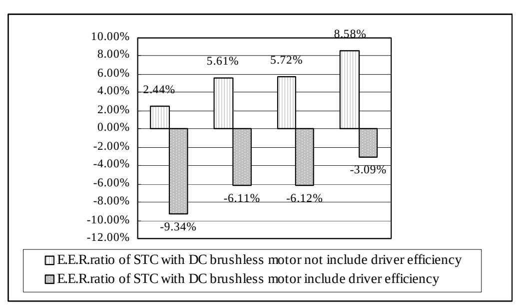
(a) Performance of STC with AC motor



(b) Performance of STC with DC brushless motor (not include driver power loss)



(c) Performance of STC with DC brushless motor (include power loss of driver)



(d) E.E.R. ratio Comparison of STC with DC brushless

Figure 5: Performance comparisons between STC with AC motor and DC brushless motor

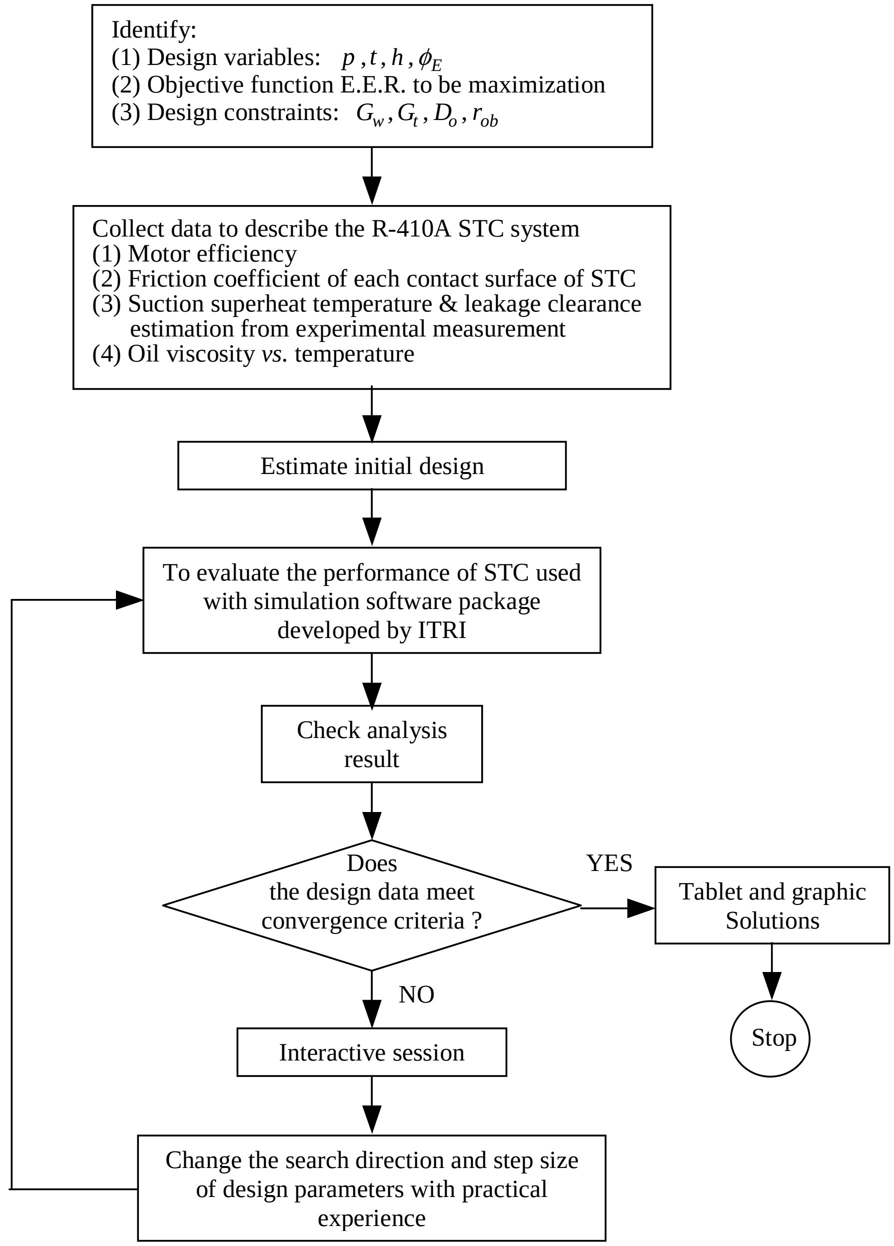


Figure 6: Optimum design process in this investigation