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PROPANE AS REAL ALTERNATIVE TO R404A REFRIGERANT IN LIGHT COMMERCIAL REFRIGERATION

PROPAN JAKO REALNA ALTERNATYWA DLA CZYNNIKA CHŁODNICZEGO R404A W LEKKIM CHŁODZENIU HANDLOWYM

A b s t r a c t

The future and sustainability of refrigeration industry is in high efficiency, low noise and operation with low environmental impact refrigerants. Continuously trend of HCFC and HFC refrigerants phase out opened research of other refrigerants alternatives to fulfill market requirements. Propane as natural refrigerant has high potential to succeed in the field of light commercial refrigeration by replacement of R404A. Thermodynamic properties of propane allow improving compressor performance comparing with R404A alternative. The study presented in this paper is focused on the proper design of discharge valve system of R290 compressors which primarily have been designed for R404A operation. The paper shows noise and efficiency improvements of light commercial compressor using propane that makes this refrigerant very attractive.

Keywords: propane compressor, efficiency, noise

S t r e s z c z e n i e

Zrównoważony rozwój przemysłu chłodniczego w przyszłości oparty jest na takich priorytetach, jak wysoka wydajność, niski poziom hałasu oraz wykorzystywanie czynników chłodniczych o słabym wpływie na środowisko. Popularność czynników chłodniczych HCFC i HFC ogranicza możliwości badań nad innymi alternatywami mogącymi spełnić wymagania rynku. Zastępujący R404A propan jako naturalny czynnik chłodniczy charakteryzuje się dużym potencjałem w zakresie lekkiego chłodzenia handlowego. Termodynamiczne właściwości propanu pozwalają podnosić wydajność sprężarek w porównaniu z R404A. Badania przedstawione w niniejszym artykule koncentrują się na właściwym projektowaniu systemu zaworów odpływowych w sprężarkach R290 opracowywanych w pierwszym rzędzie dla funkcjonowania R404A. W artykule zaprezentowano ulepszenia w zakresie poziomu głośności i wydajności lekkiej sprężarki handlowej wykorzystującej propan, które znacznie zwiększają atrakcyjność tego właśnie czynnika chłodniczego.

Słowa kluczowe: sprężarka propanowa, sprawność, hałas

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1. Introduction

The most preferred aspects in current commercial refrigeration business become reliability, noise and efficiency. Market demands for low noise commercial appliances with high efficiency are increasing significantly. Sound is a subjective parameter that is immediately perceived by customer after switching on appliance and it is directly evaluated by human hearing system. Commercial systems are also many times placed at quite ambient like hospitals and small markets that require low sound levels. Efficiency is a kind of "hidden parameter" and it is felt by end-user on his electricity bill. Efficiency of the commercial appliances becomes very important with current trend of low cost operation and rising price of energy. Application of green refrigerants in commercial appliances with low GWP is currently not a priority of manufacturers. One possibility to stimulate application of green refrigerants in commercial refrigeration instead of HFC is the legislation adjustment. As we know from the past, this is always long time process. Other smart way is to develop and promote alternative products using green refrigerants with better noise and efficiency performance comparing with HFCs. This is an excellent opportunity for engineers in refrigeration compressor development as their contribution to sustainability of refrigeration industry.

Compressor is a significant noise source in commercial refrigeration system due to high excitation from internal parts during its operation. The excitation is proportionally equal to mass flow and load on compressor mechanism. Continuous process of compressor efficiency and noise improvement is mostly trade off between them. Actions to make compressor more efficient are linked with the reduction of thermodynamic losses. Energy losses in suction and discharge processes are affected by orifices, valves and mufflers. The size of discharge

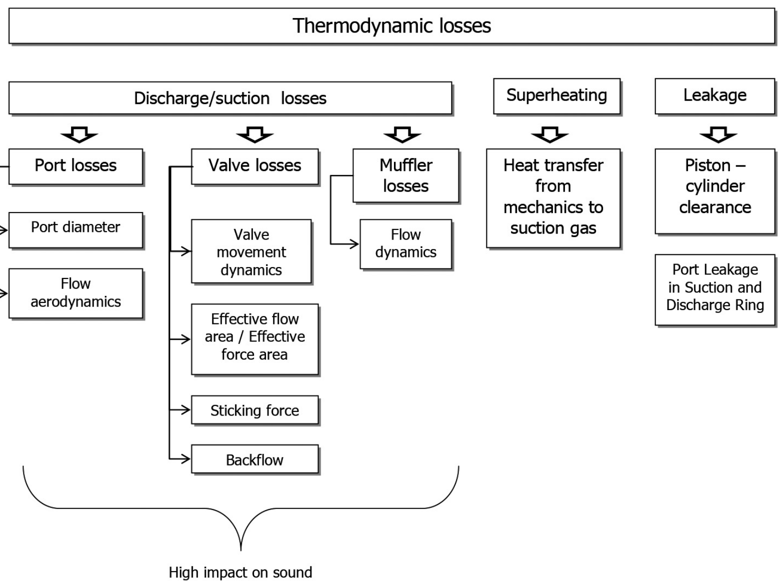


Fig. 1. Map of thermodynamic losses in the refrigeration compressor

Rys. 1. Prezentacja strat termodynamicznych w sprężarce chłodzącej valve orifices shall be designed as large as possible to reduce overpressure and velocity of the gas. The overpressure is increasing discharge losses and high velocity of the gas is increasing its friction losses when passing through the valves. However, for low back pressure applications, the discharge valve orifice shall be always compromise between energy losses and reduction of volumetric efficiency by dead volume. Suction and discharge valves control gas flow in and out of the cylinder and must meet criteria for proper dynamics with fast response and high flow rate. Special attention on valves is extremely important in compressor design because of their high impact on volumetric and compression efficiencies, noise excitation and overall compressor reliability. Activities to reduce thermodynamic losses are often increasing internal sound and vibration excitation in the compressor. In this case compressor design requires acoustic solutions and optimizations to compensate thermodynamic approach. The paper shows approach in modification of discharge valve system in the propane commercial compressor being developed from R404A mechanical baseline that improves efficiency and reduces sound power level comparing with its R404A alternative.

2. Efficiency potential analysis of propane

Propane compressor design was performed and evaluated on base of original R404A configuration. Propane and R404A refrigerants are very close considering required displacement of the compressor for the same cooling capacity at specific operating conditions. To understand potentials of the new compressor design, it is very effective to perform simple theoretical thermodynamic analysis. The main thermodynamic properties considered in the analysis are compressor size, effective power, suction and discharge losses and coefficient of performance of indicated diagram so called COP PV. Parameter COP PV can be understand as a thermodynamic efficiency and it is calculated as a ratio between cooling capacity and power spent just for gas intake, compression, exhaust (discharge) and expansion, which process is described by compressor pressure-volume diagram. The power doesn't include mechanical losses in bearings and electrical losses in motor.

$$\mathrm{COP}_{\mathrm{PV}} = \frac{Cooling\_capacity}{PVpower} \tag{1}$$

It is very convenient for better approximation to consider in the calculation real internal compressor superheating that affects suction gas density and consequently volumetric refrigerating effect. The temperature of the gas is measured in the closest possible place to the suction valve. The compressor working application in the analysis is considered as low back pressure with cooling capacity around 500 W at rating conditions according to standard EN12900. Based on theoretical calculation, the displacement of propane compressor shall be 1.19 larger than R404A configuration due to its lower volumetric refrigerating effect. The interesting results are 40% lower suction losses and 20% lower discharge losses of propane configuration. Propane version has also 8% better thermodynamic efficiency expressed by parameter COP_PV. The results of the pure thermodynamic analysis that doesn't consider several aspects like valve dynamics and real compression process shows that propane is an excellent alternative to R404A in terms of efficiency.

Table 1

Theoretical efficiency projection of propane compressor

Conditions EN12900: -35/40°C, return gas temperature 20°C, no subcooling considered

Refrigerant	R404A	R290
Capacity (Watts)	530	530
Displacement size (relative to R404A)	1	1.19
COP Ideal cycle (% difference to R404A)	ref	4.5
Effective power (relative to R404A)	1	0.96
Effective power (ΔWatts)	ref	-13
Discharge losses (relative to R404A)	1	0.79
Discharge losses (ΔWatts)	ref	-5
Suction losses (relative to R404A)	1	0.63
Suction losses (ΔWatts)	ref	-6
PV power (ΔWatts)	ref	-24
COP PV (% difference to R404A)	ref	8

3. Discharge valve system analysis

The main task of discharge valve system is to allow efficient discharging of compressed gas with reliable operating. Basically the discharge valve system is assembled on valve plate and consists from discharge valve and valve delimiter. Important parameter of discharge valve system is a valve lift. The lift is the distance that valve is travelling from its closed position on the seat until its fully opened position at the delimiter. Magnitude of valve lift has strong influence to valve movement that directly affects efficiency and reliability. Valve movement defines mass flow passing through the valve orifice and power needed for discharge process. The requirement for a good discharge valve movement is to be fully opened when reaches discharge pressure, remains fully opened during whole discharging process and being closed immediately at the time when piston reaches top dead centre position. Any valve fluctuations or delay in closing causes energy losses. Consequence of too late valve closing is undesirable backflow from discharge to suction side when discharge valve is not fully closed and discharge chamber pressure is higher than cylinder pressure. At this situation discharge gas returns back to cylinder chamber, it expands inside the cylinder, it heats the gas inside and reduces the volume available for suction process. Consequently it has a strong effect on volumetric efficiency losses and the energy consumption might be affected too.

The component that defines the valve lift is the valve delimiter. The delimiter must be designed correctly to have valve lift not so high but also not too low. Too high valve lift will cause the pressure to drop and valve can tend more to fluctuations or flutter. Moreover, too

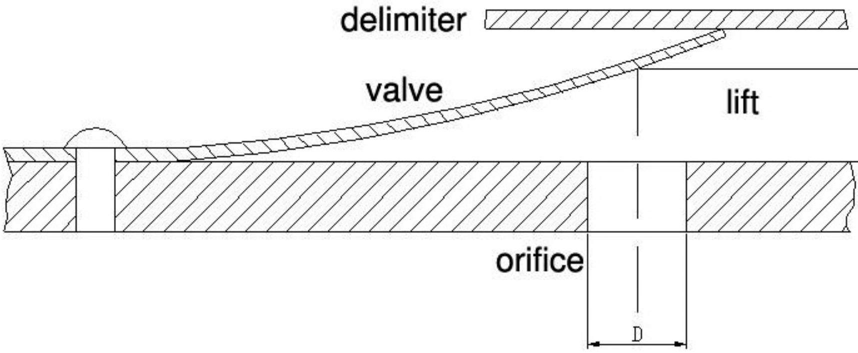


Fig. 2. Discharge system with reed valve

Rys. 2. System odpływowy z zaworem radłowym

high valve lift will cause higher impact velocities of the valve to the seat that can reduce life time of the valve. On the other hand, the lift being too low will increase excessively discharge losses that reduces efficiency of compression operation. Important factor to define valve lift is a gas density. Generally gases with high density require higher valve lift. For very small discharge valve lifts, the flow through the valve is laminar. At high valve lift, the flow is going to be turbulent with recirculation regions and it can be described by radial jet. At turbulent flow, the real gas consumes part of its energy to create swirls that reduce total velocity of the gas and flow is not stable. In the area of the swirls, the velocity of the gas increases and pressure drops. It is possible to conclude that discharge valve lift shall vary with compressor working conditions and refrigerant. This rule is a way how to control energy losses in discharge valves and optimize compressor efficiency.

Smaller discharge losses of propane configuration presented in Table 1 open space for other compressor optimization in terms of noise level. According to the theory mentioned above, it can be used lower valve lift for propane compressor comparing with R404A alternative. Lower valve lift has consequently influence to the reduction of mechanical excitation coming from the valve impact to the delimiter and to the seat.

4. Results of experiment

Optimization process of the valve lift in propane compressor was performed in terms of cooling capacity, efficiency and noise. Secondary factors like compressor startability, discharge valve movement, discharge temperature, discharge pulsation spectrum and motor temperature were analyzed as well. Optimization was done using design of experiment methodology. The result of this analysis showed that optimum valve lift for propane compressor is about 40% lower than R404A configuration at conditions of rating point in theoretical analysis. Real efficiency benefit of propane version is about 9% and it is aligned with theoretical projection of COP PV. Volumetric efficiency is better than expected and the displacement to get rated cooling capacity is lower about 9% than calculation.

Table 2

Calorimeter performance of the R404A compressor and R290 with optimized valve lift

Conditions EN12900: -35/40°C, suction temperature 20°C, no subcooling considered

Compressor	Valve lift Configuration	Capacity	Power input	EER
		[Watts]	[Watts.]	[Watts/Watts]
R404A	standard	Ref	Ref	Ref
R290	optimized	-7.1	-48.1	0.09
Difference [%]		-1.3	-9.3	8.7

Important activity to support calorimeter results is the discharge valve movement measurement in different valve lift configurations. Valve displacement is measured by proximity transducer installed in valve plate. Signal from the transducer is amplified and processed together with synchronization signal carrying information of the shaft angle. Analyzing curves of valve displacement in Fig. 3, it is possible to conclude that lower optimized delimiter improved significantly valve behavior. The valve has much more stable operation during discharging process. On the other hand the valve movement operating with propane and using delimiter from R404A compressor has big pressure drop that results in improper dynamic behavior with two strong openings.

Noise measurements of optimum configuration with reduced discharge valve lift showed improvement about 4 dB of total sound power level comparing with R404A version. This is significant change perceived by human hearing and converting dB scale to Watts means half of acoustic energy. Sound quality was positively affected too due to reduction of sound power levels in the middle and high frequency bands where the human ear is the most sensitive.

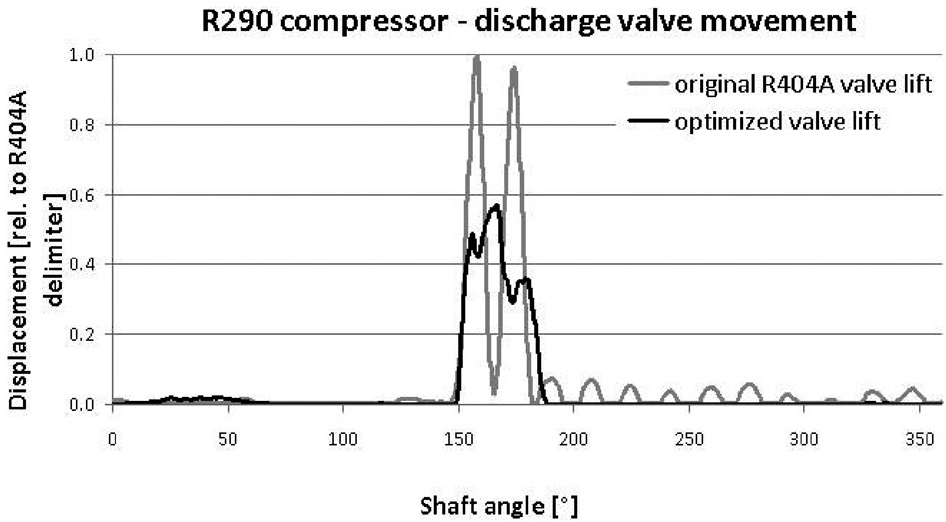
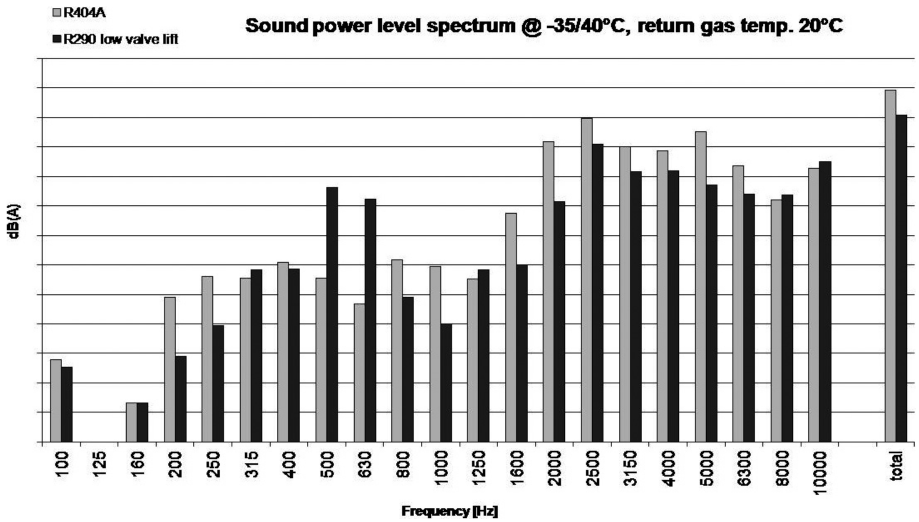


Fig. 3. Discharge valve movement analysis of R290 compressor

Rys. 3. Analiza ruchu zaworu odpływowego w sprężarce R290



Compressor	Configuration	Total noise dB(A)
R404A	standard valve lift	59.5
R290	reduced valve lift	55.5
	Difference	-4.0

Fig. 4. Sound power spectrum and total noise comparison of R290 and R404A configuration

Rys. 4. Spektrum natężenia dźwięku oraz porównanie hałasu całkowitego w konfiguracji R290 i R404A

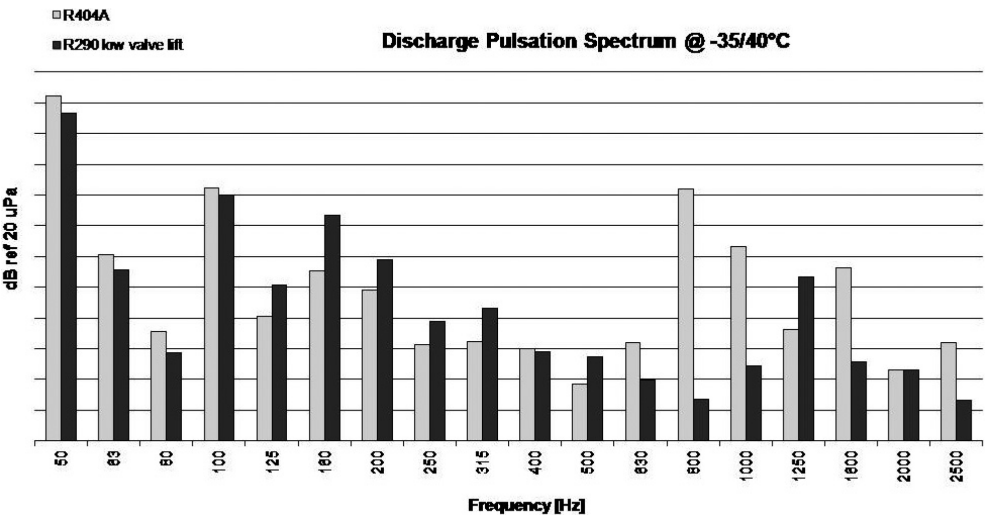


Fig. 5. Discharge pulsation spectrum comparison of R290 and R404A configuration

Rys. 5. Porównanie spektrum pulsacji odpływu w konfiguracji R290 i R404A

The discharge temperature measured in the cylinder head of propane optimized version is very similar to R404A configuration even though the valve lift was reduced. The value is aligned with theoretical calculation of the cycle considering internal superheating. Other important compressor parameter that was analyzed is a discharge pulsation spectrum. It is necessary to check pulsation spectrum as the acoustic boundary conditions of discharge muffler are changed due to higher sound velocity of the propane refrigerant. The sound velocity of the propane at specified temperature and pressure is 284 m/s against 189 m/s of R404A. The measurement of the pulsation spectrum showed reduction of energy at bands which can excite structural vibration modes in the appliance.

5. Conclusions

The paper shows example of propane compressor design built from R404A mechanical kit where efficiency and noise are in agreement High noise generated by valves operation and efficiency of discharging process can be optimized in propane low back pressure compressor. Analysis in this paper shows importance of correct adjustment of discharge valve lift by its delimiter for different refrigerants. The geometry of delimiter significantly affects valve movement and output performance of the compressor. Valve movement is a fundamental path to noise and efficiency optimization. Lower thermodynamic losses in discharge side of the compressor operating with propane allow reduction of discharge valve lift about 40% compared to R404A lift. Smaller mechanical excitation from the valve operation linked with lower impact velocities enables noise reduction about 4 dB keeping efficiency benefit of propane about 9% compared to R404A baseline configuration. This result makes propane compressor very attractive and it can convince more the customer to replace R404A by propane as natural refrigerant. Better performance in terms of efficiency and noise, improving environment by low GWP is a very high potential that allows propane to be successful in light commercial refrigeration market. Low power consumption, low noise emissions and refrigerants with small greenhouse effect is a future and sustainability of commercial refrigeration business.

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