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Development of Energy Efficiency Design Map based on acoustic resonance frequency of suction muffler in compressor

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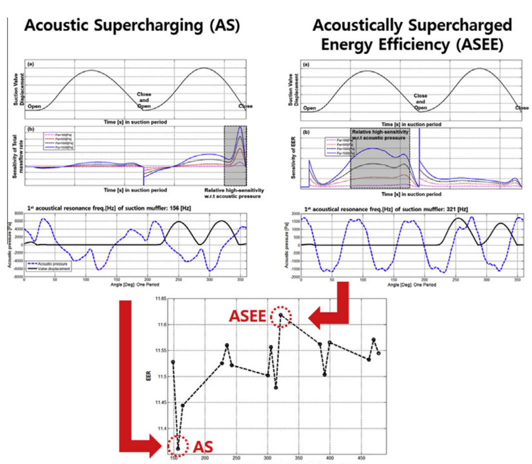
HIGHLIGHTS

- Development of Energy Efficiency Design Map.
- Experimental validation of Energy Efficiency Design Map.
- Suggestion regarding the Acoustically Supercharged Energy Efficiency.
- Sensitivity analysis of the Energy Efficiency Ratio with respect to acoustic pressure.
- Suggestion regarding the hybrid coupling method for acoustic analysis in compressor.

GRAPHICAL ABSTRACT



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ABSTRACT

The volumetric efficiency of the Internal Combustion (IC) engine and compressor can be increased by properly adjusting the acoustic resonance frequency of the suction muffler or the suction valve timing without any additional equipment or power source. This effect is known as acoustic supercharging. However, the energy efficiency has become more important than the volumetric efficiency because of the energy shortage issue and factors influencing consumers' purchasing decisions. Therefore, methods for increasing the energy efficiency using the acoustic effect in the suction part of IC engine and compressor should be considered. In this study, a systematic method for improving the energy efficiency using the acoustic effect in the suction part of the compressor used in refrigerators and air conditioners was developed for the first time. This effect is named as the Acoustically Supercharged Energy Efficiency (ASEE). For the ASEE, first, a hybrid coupling method was suggested for the acoustical analysis in the suction part of the compressor. Next, an Energy Efficiency Design Map (EEDM) was proposed. This can serve as a design guide for suction mufflers in terms of the energy efficiency. Finally, sensitivity analyses of the Energy Efficiency Ratio (EER) and total massflow rate with respect to the acoustic pressure were conducted to identify the relationship between the acoustic pressure and the suction valve motion. This provides the physical background for the EEDM.

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Nomenclature

A_{flow}	effective area flow	$\mathbf{Z}_{input}$	input impedance
A_{force}	effective force area	c	speed of sound (m/s)
$\dot{m}_v$	mass flow rate (kg/s)	k_0	wave number
P_d	pressure at downstream (Pa)	α	attenuation factor
P_u	pressure at upstream (Pa)	L	length of suction muffler (m)
P_a	acoustic pressure (Pa)	ξ	viscothermal friction
T_d	temperature at downstream (K)	M	mach number
T_u	temperature at upstream (K)	r	radius of suction muffler (m)
n	ratio of specific heats	μ	coefficient of dynamic viscosity (kg/ms)
R	gas constant (J/kg K)	F	Froude's friction factor
h	lift displacement of the suction valve (m)	d	diameter of suction muffler (m)
$\mathbf{M}$	mass of suction valve	Re	Reynold's number
$\mathbf{C}$	damping of suction valve	W	scale factor
$\mathbf{K}$	Stiffness of suction valve	ω	angular frequency (rad/s)
ρ_d	density in cylinder (kg/m^3)	t	time (s)
V	cylinder volume (m^3)	δ	delta function

1. Introduction

The volumetric efficiency of the Internal Combustion (IC) engine can be increased by properly adjusting the acoustic resonance frequency of the suction muffler or the suction valve timing without any additional equipment or power source. This effect is known as acoustic supercharging. Using the acoustic supercharging effect, it is known that the volumetric efficiency of the IC engine in automobile can be increased from 15% to 30% [1–4].

The representative studies on acoustic supercharging with IC engines in automobile are as follows. Morse et al. [5] noted that supercharging effect occurs if the valve only closed when the pressure was greater than atmospheric pressure. Rubayi [6] measured the volumetric efficiency by changing the length of the suction pipe. Thus, the maximum supercharging effect was achieved when the ratio of the resonance frequency of the intake pipe was approximately twice the engine speed. Harrison and Dunkley [7] mentioned that the supercharging effect was related to engine speed. In other words, inertial ram effects strongly contributes to the intake process at high engine speeds, whereas acoustic resonance effects are more significant at low engine speeds. Recently, the acoustic effect in intake system was analyzed using the coupling method with a mechanical analogy. This was proposed by Rodriguez et al. [8]. Furthermore, the variations of volumetric efficiency depending on the engine speed were investigated. D'Errico et al. [9] performed optimization to improve the volumetric efficiency with the length of the intake pipe using a 1D fluid dynamic analysis model. In addition, Mezher et al. [10] proposed a transfer function between the acoustic pressure and the volume velocity. In the transfer function, the inertial ram effect and damping were considered. Using the transfer function coupled with GT-Power, the acoustic pressure in the intake system was accurately predicted to improve low end torque and increase mass flow rate. Recently, in order to increase the volumetric efficiency, the acoustic supercharging effect was applied to the hydrogen internal combustion engines and the Homogeneous-Charge Compression-Ignition (HCCI) engines as well as the IC engines [11–13].

The acoustic supercharging effect was applied to not only automobile engines but also compressors used in refrigerators and air conditioners.

The representative studies on acoustic supercharging in compressor are as follows. Mozzon and Genoni [14] conducted an experiment by changing the suction pipe length. According to the experimental results, the supercharging effect was maximized when the resonance frequency of the suction pipe is approximately twice the excitation frequency. In addition, Liu and Soedel [15] investigated the factors that can affect compressor performance. One of the factors is the acoustic supercharging effect. Based on his investigation, the volumetric efficiency can be increased by acoustic supercharging. However, because the amount of work done by the piston simultaneously increases, the overall compressor efficiency can decrease. Akashi et al. [16] investigated how waves propagated in the suction pipe of a compressor using the method of characteristics. To experimentally confirm acoustic wave propagation in the suction pipe, several piezoelectric pressure sensors and displacement sensors were installed. As a result of the experiment, the return timing of the acoustic pressure wave in the suction pipe and the open and close timing of the suction valve were confirmed to be an important pair of factors determining the acoustic supercharging effect. Furthermore, the acoustic supercharging effect was investigated using the Computational Fluid Dynamic (CFD) by Suh et al. [17]. Park [18] proposed a transient simulation model of a rolling piston type rotary compressor and volumetric efficiency was calculated with respect to variation of the driving frequency.

Based on the representative studies on acoustic supercharging in compressor, most studies aimed to increase the volumetric efficiency. However, in recent years, the energy efficiency of refrigerator or air conditioner has become an increasingly important issue due to the shortage of energy resources. In addition, the most important one of factors influencing consumers' purchasing decisions is energy efficiency [19,20]. Therefore, a method for increasing the energy efficiency instead of improving only the volumetric efficiency of compressor should be developed. In general, the energy efficiency of compressor can be represented by Energy Efficiency Ratio (EER). This is defined as the ratio of the cooling capacity to the input power [21]. In contrast with EER, input power is not considered in volumetric efficiency. Recently, there are studies to improve the EER of compressor. Gonzalez-Ramirez et al. [22] investigated potential energy saves in an ice cream freezer by using a variable speed compressor and optimization methodology for operating conditions during the process. In addition, Long et al. [23] developed the novel reverse cycle defrosting method for increasing the EER. However, until now, there is no research on acoustic supercharging to increase the EER of compressor. Therefore, in this study, a systematic method for increasing the EER of compressor was proposed. This is named as Acoustical Supercharged Energy Efficiency (ASEE). This is introduced for the first time by the present study.