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Feature Article: Refrigeration and Cryogenic Technologies - The 20 K Refrigeration System Development and Hydrogen Engines Automobiles

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Refrigeration and cryogenic technologies are indispensable for applications such as medical, which have superconducting magnets for MRI (Magnetic Resonance Imaging), for space applications, where the re-liquefaction of helium gas is required to cryocool the telescopic cylinder of infrared telescopes, and for ground applications such as power transmission, linear maglev Shinkansen and the liquefaction of gas.

There are concerns associated with the depletion of fossil fuels and the consequent release of toxic exhaust gas such as carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxide (NO_x) when an internal combustion engine burns this fuel, (hitherto known as engine). In order to solve these issues, Tokyo City University (former Musashi Institute of Technology), has investigated hydrogen fuel as an alternative fuel source to fossil fuels. In 1970, under the guidance of the late Professor Shoichi Furuhama (former President of Musashi Institute of Technology), Mr. Masaharu Yuasa, my colleague, and I began research into hydrogen engines, or more specifically, how hydrogen fuel characteristics affect engine.

The primary energy source of hydrogen is natural energy, namely solar energy such as sunlight, Sun's heat, wind, hydropower and wave power including geothermal power and wave power. as well as the abundant water on the earth. The burning of hydrogen and air does not produce the emission of greenhouse gases such as carbon dioxide (CO_2). Strictly speaking, engines require hydrocarbon-based lubricants in similar way when the fossil fuels are used. The lubricants burn with hydrogen fuel producing up to 15 ppm of CO_2, CO and HC. And, as hydrogen is burnt with air, the emission of NO_x in the exhaust gas is dependent upon the operating conditions. However, the volume of greenhouse gases emitted from the exhaust gas is so small that it is not a source of pollution. The initial car engine test carried out at the institute showed that hydrogen fuel could be used as an alternative one to fossil fuels. To demonstrate this, a total of 12 hydrogen engine automobiles were developed. Recently, the technical standard of high pressure light-weight hydrogen gas cylinders fabricated by filament winding for the hydrogen fuelled vehicles has been established. That allows the automobiles to run the public roads with white number-plates on. An automobile equipped with a lightweight composite cylinder including hydrogen supply system for 35 MPa high-pressure hydrogen gas has made demonstration tests on the public roads. However, technical standards for the liquid-hydrogen fuel supply system have not yet been taken into consideration but will be discussed later in this report. It is hoped that these technical standards will be prepared in the not too distant future.

Essential requirements for automobile engines are lightweight, compact, high power output and low cost. To satisfy these conditions using hydrogen fuel, the fuel needs to have a high energy density. This technology is very difficult to achieve in principle, however an analogous hydrogen supply system has already been tested in our laboratory. This system utilizes a liquid hydrogen pump producing pressurized liquid hydrogen on board. The liquid hydrogen is gasified by using the heat of ambient air and engine cooling water. The

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gas at high pressure is directly injected into the combustion chamber of the engine. This prevents the occurrence of abnormal combustion. Moreover, the system produces power outputs,1.2 times greater than engines operating on fossil fuels. By further optimizing the hydrogen fuel drive engine operation, it is expected that the thermal efficiency will improve when compared to engines operating on fossil fuels. Thus, utilizing liquid hydrogen fuels will create an ideal hydrogen engine automobile [1].

However, when using a standard fossil-fuel tank for liquid hydrogen storage, the liquid hydrogen would soon evaporate and vanish after it is put into the automobile. If, however, the liquid hydrogen remains in the fuel tank, it becomes pressurized owing to the evaporation and has a potential explosive hazard. Adequate insulation is required, but complete thermal insulation is physically impossible. Linde company developed a liquid hydrogen fuel tank having a hydrogen storage capacity of around 100-130 liters with the smallest evaporation loss of 1 % per day for BMW hydrogen fuel cars. However, despite these superior characteristics, this ultra-adiabatic tank proved unfeasible for automobiles from a cost point of view. The evaporation loss for a practical liquid hydrogen fuel tank is estimated to be around 5 % per day. In the future automobiles will have greater intelligence and require more electric power than now. So that BMW, liquid hydrogen fuelled engine vehicle company, they have a plan to capture and utilize the boil-off hydrogen gas. And they convert it to electricity by a small size onboard fuel cell. Even this method cannot solve the problem of the loss of liquid hydrogen in the tank. It is definitely true that the drivers do not want to have the liquid hydrogen in the tank lost while their cars are not used such when the cars are at parking lots and garages. The pressure in the tank of automobiles fuelled by liquid hydrogen hardly increases during driving. Because the hydrogen gas evaporated in the tank is utilized as the fuel while the engines are running. Research has been on-going in the development of a system to store the evaporated hydrogen gas using hydrogen-absorbing alloys, which could then be used, for example, to fuel automobile when the car is driven[2]. However hydrogen-absorbing alloys have their storage limitations and the issues still remain unsolved while cars are not driven for long periods of time.

Apart from the original initiative of utilizing naturally evaporated liquid hydrogen as an automobile fuel, a study was carried out to find out which was cheaper, refuelling the same amount of liquid hydrogen as that of the liquid hydrogen naturally evaporated out to the atmosphere, or utilizing electricity to drive a cryo-cooler to reliquefy the evaporated hydrogen gas. Figure 1 shows the cost comparison between the cost of electric power for liquefaction and the liquid hydrogen cost for refuelling. The horizontal axis shows the evaporation loss volume (% per day) of a 100 liter fuelling capacity tank, and the associated costs are on the vertical axis. Calculations of liquid hydrogen fuelling costs are based on a selling price per litre. For the costs of the refrigeration system, the efficiency data were obtained from a commercialized small-type GM cycle refrigeration systems and then the calculation for the cost was made. The cheapest price of liquid hydrogen fuelling cost, as planned at the

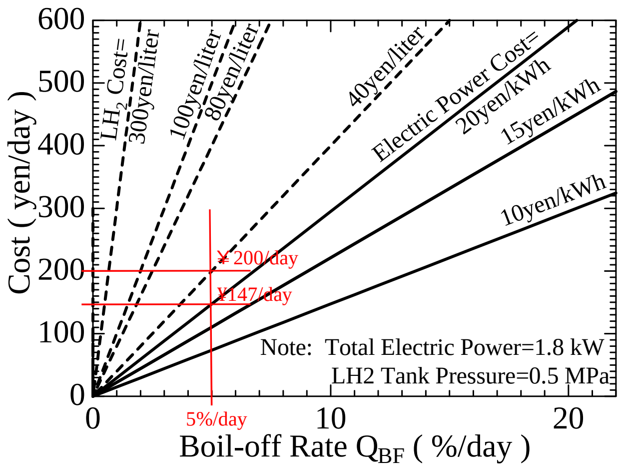

Fig. 1 Cost comparison between the cost of electric power for liquefaction and the liquid hydrogen cost for refuelling

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Euro-Quebec Hydro-Hydrogen Project, was 40 yen/liter. Unfortunately, this has yet to be realized. However it is the cheapest price of liquid hydrogen that the author is aware of. The most expensive selling electricity price is that paid by households, priced at 20 yen/kWh. The typical evaporation loss of liquid hydrogen for hydrogen fuelled automobile use is around 5 % per day. Then the evaporation loss makes it 200 yen per day to refill the amount of the evaporated liquid hydrogen into the tank. Even when using the expensive electricity, the cost is only 147 yen per day when utilizing the cooling system with the efficiency data mentioned above. The cost of the electricity power is still cheaper compared to the cost of refuelling the amount of the evaporated liquid hydrogen. In 2002, our research was selected for the innovation task under the WE-NET program, commissioned by NEDO. Professor Yoichi Matsubara was the main member as he held the world's authority on pulse-tube refrigeration. And ten researchers who had interests in the field launched the project aiming at reducing the evaporation of the liquid hydrogen fuel loss to zero. An initial feasibility study was undertaken to investigate and select a compact refrigeration system to match the requirements for automobiles. Table 1 shows the results of the study. It was understood that the pulse-tube refrigeration system was deemed most suitable as a refrigerator for use in automobiles.

The successful development of the small cryo-coolers for reduction of liquid hydrogen evaporation loss to zero is a synonym for realization of an ideal automobile engine fuelled by liquid hydrogen and available for practical use. The project started in 2002, however, the majority of the research and development was carried out with liquid helium or liquid nitrogen refrigeration systems, with nothing for liquid hydrogen. It was repeatedly proposed that the pulse-tube refrigeration system was deemed the most suitable candidate for hydrogen-powered automobile engines, however, there were difficulties in accepting these proposals. Eventually, in 2008, experiments towards the realization of zero evaporation loss in liquid hydrogen got underway under an "exploratory research" provided by a grant-in-aid, sponsored by the Ministry of Education, Culture, Sport, Science and Technology and as "precedence priority research" at our university.

Table 1 Comparison of the Characteristics of Compact Cryo-coolers

Type	Characteristics	Adaptability to Cars			
		Compact & Light weight	Long Life	Simple Structure	Easy Operation
Micro-Joule Thompson Cryo-cooler	◆A few tens of MPa pressure gas required ◆Easy use because of light weight ◆Low vibration, low noise because of no moving parts	○	○	○	× (High Pressure Required)
Regenerative Cryo-coolers ⊙Stirling cycle ⊙ Vuilleumier cycle ⊙GM cycle ⊙Solvay cycle	◆Large Compressor required ◆Occurrence of vibration ◆Long start-up time (about 10 minutes) ◆Heavy, Large ◆Switching valves required	×	△	×	× (Large Compressor Required)
Pulse-tube Cryo-cooler	◆Simple structure ◆No moving parts ◆No vibration ◆High reliability to long operation	○	○	○	○

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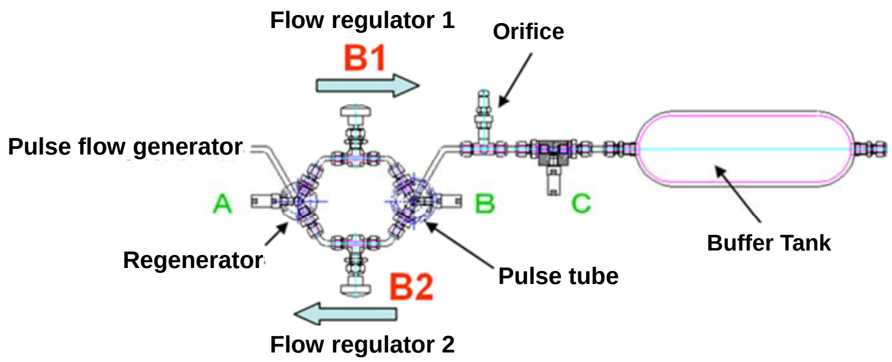

A : Regenerator pressure gauge
B : Pulse tube pressure gauge
C : Buffer tank pressure guage

B1 Cv max 0.37
B2 Cv max 0.37
Orifice Cv max 0.03

Pulse tube shape		Regenerator shape		Pulse moderator	
-Length	194 mm	-Length	120 mm	- Capacity	2 ℓ
-External diameter	20 mm	-External diameter	30.5 mm		
-Internal diameter	19 mm	-Internal diameter	30.0 mm		

Fig. 2 Schematic Diagram of the Prototype single-stage pulse-tube cryo-cooler fabricated

The funds allowed researchers to have a dedicated laboratory and begin the fabrication of a prototype system utilizing a pulse-tube refrigeration system. Fortunately, we also received guidance from Professor Yoichi Matsubara, leading to an initial prototype, single-stage pulse-tube refrigeration system, as shown in figure 2. Since then, the experiments for pulse-tube refrigeration system were carried out and research towards the realization of zero evaporation loss of liquid hydrogen has been advancing. Figure 3 shows the complete view of the prototype single-stage pulse-tube refrigeration system. For the time being, the targeted operational performance of the pulse-tube refrigeration system is to obtain 1W cooling energy against an input electric power of 300 W. In the future, the target would be to obtain 1W cooling energy at an electric power input of 100 W. Considering that the system components are almost the same as those used for the home refrigerators, the cost of the pulse tube cryo-cooler would be less than 100,000 yen when under the mass production.

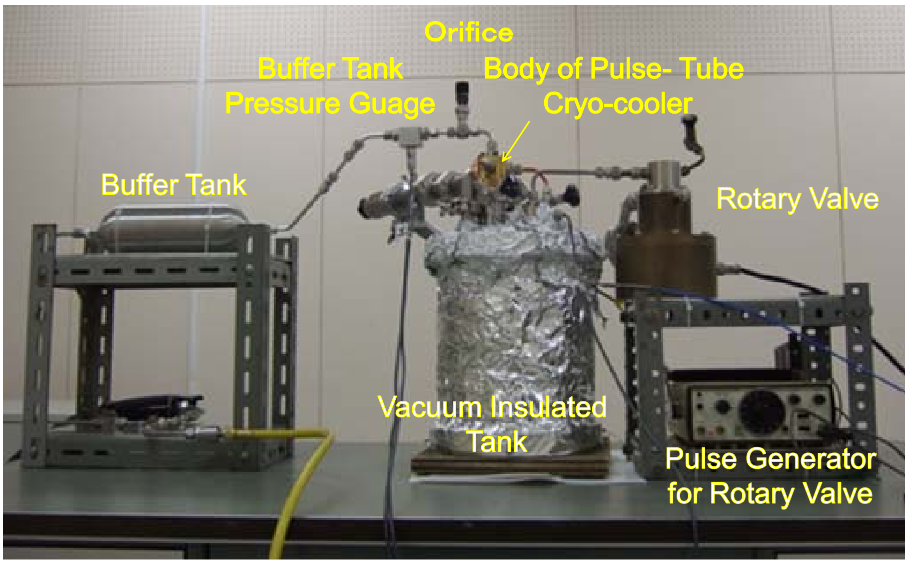

Fig. 3 Photo of the Prototype Pulse-Tube Cryo-cooler Installed on Test Bench

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