Development of a kw-class Stirling cryocooler for liquefaction of natural gas (NG)

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Abstract. Our research group has developed a kW-class Stirling cryocooler. The Stirling cryocooler adopts a ‘gamma-type’ configuration operated with a linear compressor. The cold-end of the Stirling cryocooler is equipped with heat exchangers that can accept and eventually liquefy natural gas (NG). The liquefied natural gas (LNG) is stored in an auxiliary reservoir. In this research paper, the experiments as a proof of concept have been carried out. The Stirling cryocooler has been independently tested prior to adopting the heat exchanger as the aforementioned above. It has been confirmed that the Stirling cryocooler can exert over 1 kW cooling capacity at 110 K cold-end temperature with 9 kW compressor input. This research paper mainly focuses on (1) relevant technical issues during the cooler development process and (2) demonstrating the liquefaction of argon gas (instead of using NG for the sake of safety regulation). The system presented in this paper, therefore, can be a good candidate for a small-scale liquefier does not require oil-involved maintenance.

1. Introduction
As the Paris Agreement has taken effect as of 2015, most of the countries are being forced to mitigate greenhouse gases (GHG). At this point, the demands of low-carbon involved resources are imperative nowadays. The renewables containing low- or zero- carbon will be alternative for the significant portion of present sectors of electricity and transportation in near future. Typically, hydrogen and methane (natural gas, NG) can be good candidates for an energy carrier purpose. In order to become an energy carrier, it can not only be stored easily, but it can be shipped via liquid form as the same way it was shipped by oil. Unfortunately, since they have very low boiling point, i.e. 110 K for NG and 20 K for hydrogen, so that efficient liquefaction cycle would be imperative.

In this research paper, we will introduce our Stirling cryocooler which is driven by a linear compressor unit. The Stirling cryocooler adopts free-piston and gamma configurations. The cooler has been tested independently to understand its thermal/dynamic behaviour. After that, liquefaction of NG has been demonstrated by installing auxiliary heat exchangers at the cold-head of the Stirling cryocooler in connection with a LNG storage vessel.
2. Test facility

The developed Stirling cryocooler is mainly composed of a dual-opposed linear compressor and a cryostat. The detailed descriptions on the Stirling cryocooler can be found in the previous publication [1]. In this paper, the liquefaction capability of the Stirling cryocooler was investigated. The Stirling cryocooler is now being equipped with heat exchanges at its cold-head and they are connected with a storage vessel. The storage vessel can contain liquefied natural gas (LNG) by the Stirling cryocooler and all the cold parts are thermally insulated with vacuumed environment. Figure 1 depicts the schematic and photo of the test facility.

Figure 1 (a) Schematic, (b) photo of the Stirling cryocooler integrated with LNG storage vessel and (c) heat exchangers installed inside the cryostat
2.1. Linear compressor
The linear compressor has two identical linear motors. They face each other and cancel mechanical vibration that originated from their movements. The linear motors were connected in parallel and each has a resonance capacitor to reduce the supplied voltage at the power source. In other word, the capacitor makes the power factor to be unity. The rated voltage, current and the resultant thrust were designed to be 380 Vrms, 15.8 A rms, (7.9 A rms, per each linear motor) and 135 N A⁻¹, respectively. The resultant electric input was to be 9 kW (4.5 kW per each linear motor) at the frequency of 45 Hz. The piston and cylinder body were made of aluminum. A set of flexure bearings are utilized at one side of the piston to reduce mechanical friction. Compared to the results of our previous work, the input power was slightly reduced without any changes and it is thought caused by an aging effect.

2.2. Cryostat
The cryostat consists of a displacer, a regenerator and a cold-head. The displacer and regenerator were designed to operate exceeding the cooling power of 1 kW at the temperature of 110 K. As a rule of the thumb, the displacer was tuned to behave with a relative phase angle of 60º to the compressor’s piston. In this research, the pre-existing cold-head was modified to install auxiliary heat exchangers accepting and liquefying the feed gas from the outside of the cryostat. The liquefied gas is now being transferred to a storage vessel. During the liquefaction process, the cold-head temperature was controlled by twelve cartridge heaters (HTR-25-100, Lakeshore) to maintain the surface temperature of the heat exchangers to be 110 K. Diode sensors (DT-670A, Lakeshore) were used and the temperature was controlled by a PID logic (Model 350, Lakeshore). The heat exchanger unit is mainly divided into two parts, i.e. for precooling (HEX#1) and subcooling (HEX#2) purposes. As single unit of heat exchanger, HEX#1 and HEX#2 was connected in serial. Two sets of the heat exchanger unit were utilized and the maximum capability of liquefaction rate was designed to be 0.1 ton day⁻¹ of LNG. The heat exchangers were installed at the four sides of the rectangular shaped cold-head.

2.3. LNG storage vessel
The LNG storage vessel has an inner and outer tanks. The inner tank is actually containing LNG that liquefied from the Stirling cryocooler and it was made of stainless steel (ASTM 304) to withstand the inner pressure of 2 MPa coping with the pressure vessel code (ASME). The volume of the inner tank is 20 L. In this research, due to the safety regulation of our institute, 0.7 MPa-argon gas was used for demonstration instead of using NG. At the pressure, boiling temperature of argon is to be 110.7 K. Therefore, the LNG equivalent liquefaction rate was obtained by considering the sensible and latent heats of argon. In order to measure the level of the liquid, a differential pressure transducer (Model DWS, SENSYS) was installed as well as six diode sensors (DT-670C, Lakeshore) were installed at the outer surface of the inner tank to divide its total height equally. The outer tank was evacuated under 10⁻⁴ torr and 50 layers of multi-layer insulator (MLI) were installed at the interlayer between the outer and inner tanks. On the top flange of the vessel, vacuumed transferring and boil-off gas venting lines were located. As aforementioned at the previous section, the vacuumed transferring line was connected with the cold-head of the Stirling cryocooler. At the outlet of the venting line, the pressure of the inner tank was manipulated. By measuring the flow rate of the feed gas, the liquefaction efficiency that influenced by such as heat exchangers’ efficiency and the thermal insulation performance was estimated.

3. Experiments

3.1. Preliminary test
Prior to the liquefaction test, we have carried out the heat load test of the cold-head. As the voltage applied to the linear compressor, the cold-head begins to be cooled down. Once the temperature of the cold-head was stabilized, both the refrigeration and electric input were recorded in the voltage range between 260 Vrms and 300 Vrms, as shown in Figure 2. At the maximum voltage, 7.26 kW-electric
input and 1.1 kW-refrigeration at 110 K were achieved. Figure 3 shows some important phase angles of the Stirling cryocooler. Where $\phi_1$ and $\phi_2$ denote the phase angle of the pressure and the displacer’s movement relative to movement of the piston, respectively. The pressure phase, $\phi_1$, is very informative to understand how much the pressure-volume (PV) work is delivered to the Stirling cryocooler effectively. On the basis of our insight, the pressure angle is to be $30^\circ$. This fact specifies that the cryostat has a proper gas impedance, i.e. damping and stiffness. $60^\circ$ of the relative movement between the piston and displacer, $\phi_2$, is suitable for free-piston Stirling cryocooler. When $\phi_2$ is larger than $60^\circ$, the displacement of the displacer becomes small. On the other hand, when it becomes close to zero the displacer cannot produce refrigeration effect. The figure shows that the values of $\phi_1$ and $\phi_2$ to be $30^\circ$ and $66^\circ$, respectively.

3.2. Liquefaction test

Figure 4 shows the cooling down history of the auxiliary heat exchangers, LNG storage vessel and the cold-head of the Stirling cryocooler. Argon gas was being entrained in all the flow channels of the system without its flowing until the cold-head was cooled down to the temperature below 110 K. During the test, the cooler was not operated with its maximum input power (equivalent refrigeration of...
0.3 kW, not 1.1 kW) so that initial cooling was relatively slow. Therefore, the liquefaction rate of argon can also be expected to have approximately 0.03 ton day\(^{-1}\). After cooled down completely, the supplied gas entered HEX1 and HEX2 and then it eventually be kept below as 4 K (2 K by HEX1 and 2 K by HEX2, respectively) compared to the corresponding saturation temperature. The temperature at the bottom of the internal tank remained to be approximately 110 K. Figure 5 shows the level increment during the liquefaction test. The average level increment was measured to be 0.0048% s\(^{-1}\) and it is equivalent to the mass flow rate of 1.2 g s\(^{-1}\) (0.03 ton day\(^{-1}\)). This result is not so different from 1.27 g s\(^{-1}\) obtained using the mass flow meter.

4. Conclusions

Thus far, we have tested a Stirling cryocooler driven by a linear compressor and then demonstrated liquefaction of natural gas (NG). Prior to the liquefaction test, the Stirling cryocooler has been tested independently. The Stirling cryocooler can exert refrigeration of 1.1 kW at 7.26 kW-electric input. Dynamic characteristics of the Stirling cryocooler was also investigated to verify whether the cryocooler operates at normal condition or not. Argon was used to demonstrate liquefaction of NG. The experiment results show that the liquefaction rate was to be 0.03 ton day\(^{-1}\) and it was also confirmed not so different compared to the mass flow rate obtained by a mass flow meter.

5. References

[1] J. Park et al., “Development and parametric study of a 1kW class free-piston stirling cryocooler (FPSC) driven by a dual opposed linear compressor for LNG (Re)liquefaction,” Int. J. Refrig., vol. 104, pp. 113–122, Aug. 2019.

Acknowledgments

This work was supported by the Basic Research of Korea Institute of Machinery and Materials (KIMM).