Study for Continuity of SPICA Cryogenic System Cooling Operations by Adding Refrigerant Circulation

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ABSTRACT

The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) is a pre-project mission of JAXA to launch a large infrared observatory to the second Sun–Earth Lagrangian liberation point (L2). A unique feature of the SPICA cryogenic system is a warm launch system using radiative cooling and numerous mechanical coolers in orbit to cool the 2.5 m telescope to less than 8 K and its detectors to sub-kelvin temperatures. SPICA uses two sets of 1 K Joule–Thomson (1K-JT) coolers and two sets of 4 K Joule–Thomson (4K-JT) coolers with three sets of double-stage Stirling (2ST) coolers, respectively used as pre-coolers for redundancy and reliability. Additionally, two 2ST coolers cool the telescope shield. The pre-coolers for 1K-JT cooler must be separated from 4K-JT cooler because of the influence of the pre-cooler's failure and necessary pre-cooling temperatures for 1K-JT coolers lower than that for the 4K-JT cooler.

This paper describes improvement for continuity of cooling operation of SPICA cryogenic systems by adding refrigerant circulation systems. The added refrigerant circulation systems increased the redundancy and reliability of the SPICA cryogenic system. As additional effects, the pre-coolers are decreased. The arrangement limitations of the thermal link and heat exchanger assemblies are also decreased.

INTRODUCTION

The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) is proposed as the Japanese infrared observatory with the following scientific objectives: 1) to elucidate the birth and evolution of galaxies, 2) and planetary system formation processes. For these objectives, SPICA is expected to provide imaging and spectroscopic capabilities at 5–210 μm wavelengths with a 2.5 m telescope cooled to a temperature below 8 K and its detectors to sub-kelvin temperatures[1, 2]. A new concept for the SPICA cryogenic system is a warm launch approach, meaning that the scientific telescope assembly (STA) includes a 2.5 m telescope and that the focal plane instrument assembly (FPIA) is warm when launched, but that it cools in orbit. Figure 1 present the mechanical cooling system used for the SPICA payload module[1, 2]. The telescope and the FPIA are cooled to deep space temperatures by multi-stage radiation and by numerous mechanical coolers. This system obviates the need to launch a large and heavy vacuum vessel. The scientific instruments of SPICA are SPICA Mid-infrared instruments (SMI), a SPICA far-infrared imaging spectrometer (SAFARI), and a Magnetic field explorer with BOlometric Polarimeter (B-BOP). The operating temperature of SMI detectors must be lower than 2 K. From these perspectives, a 1 K Joule–Thomson (1K-JT) cooler in a mechanical cooler system is also used as a 1.7 K heat sink.

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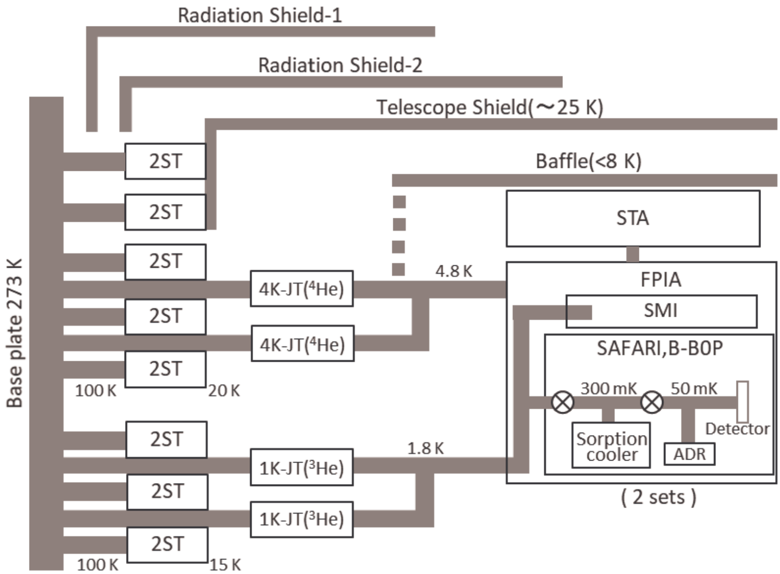

Figure 1. Mechanical cooling system for SPICA payload module.

The operational temperature of detectors in SAFARI must be 50 mK. A heat sink should be prepared to operate at a temperature lower than 4.5 K. Two sets of the 4K-JT cooler and two sets of the 1K-JT cooler are used for redundancy. The three double-stage Stirling coolers (2STs) are used respectively as pre-coolers of the 4K-JT and the 1K-JT cooler. SAFARI and B-BOP are proposed to use two sets of sub-K coolers to make 50 mK from a 1K-JT and 4K-JT cooler heat sink. The sub-K cooler consists of the adiabatic demagnetization refrigerator (ADR), which can provide 50 mK of operational temperature from 300 mK, and a ^{3}He sorption cooler as a pre-cooler of the ADR. Two sets of the 4K-JT coolers are also used to cool the baffle surrounding the STA in addition to radiative cooling. Additionally, two sets of 2ST coolers are used to cool the telescope shield actively using radiative cooling. The 4K-JT and 2ST coolers are based on the developed model for ASTRO-H[3]. The 1K-JT cooler is regarded as an engineering model under environment and lifetime tests[4].

PROPOSED REFRIGERANT CIRCULATION SYSTEM

Two types of newly conceived refrigerant circulation systems (RCS) for improving the continuity of cooling operations of SPICA cryogenic system are proposed as shown in Figure 2 and Figure 3. Although three pre-coolers are needed for the two sets of 4K-JT coolers (or 1K-JT coolers) in Figure 1, only two pre-coolers are used in Figure 2 and Figure 3.

Flow Diagram of Proposed Refrigerant Circulation System

Figure 2 portrays a Type 1 system flow diagram with two refrigerant circulation systems (RCSs) added independently to two sets of a 4K-JT cooler with a pre-cooler. The 4K-JT cooler can be replaced by 1K-JT cooler in Figure 2. The RCS facilitates heat exchange between the JT cooler and the pre-cooler. One RCS comprises two circulation pumps, two sets of two-stage heat exchanger (C-HEX 1 and 2), and two sets of two-stage heat exchangers (J-HEX 1 and 2), which exchange heat between the JT cooler and the RCS. These four two-stage heat exchangers and a pre-cooler can be connected by long stainless tubing with small diameter and thin walls to reduce heat conduction loss. Six latch type solenoid valves and four pressure transducers are equipped in adding the two RCSs. When the mass flow rate (mc) in the RCS is close to the mass flow rate (m) of JT cooler, the circulation pump can be operated by only several watts of input power to the pump because there is no large pressure drop as there is with the orifice in the JT cycle.

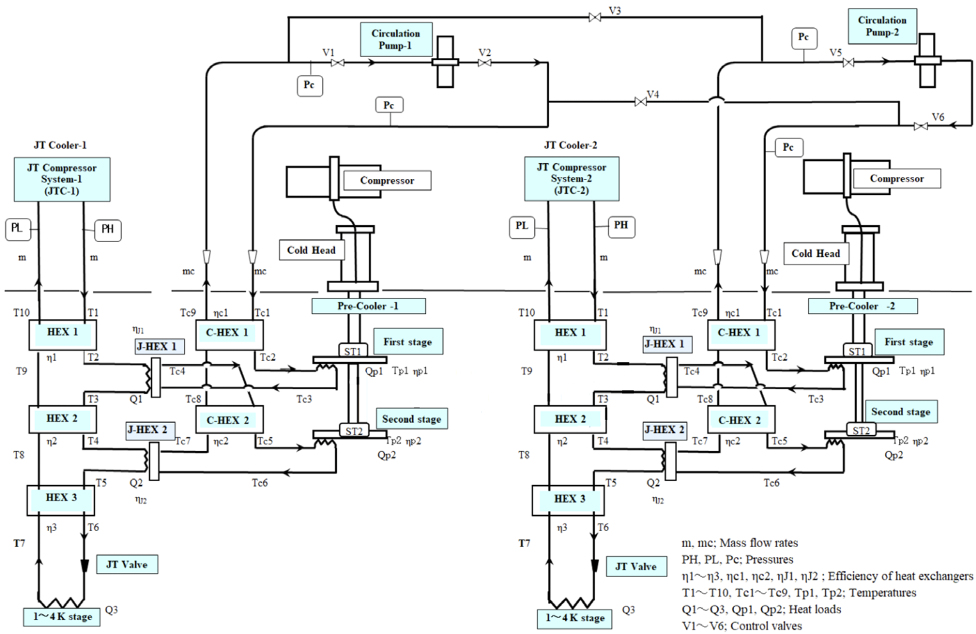

Figure 2. Type-1 flow diagram of proposed refrigerant circulation systems.

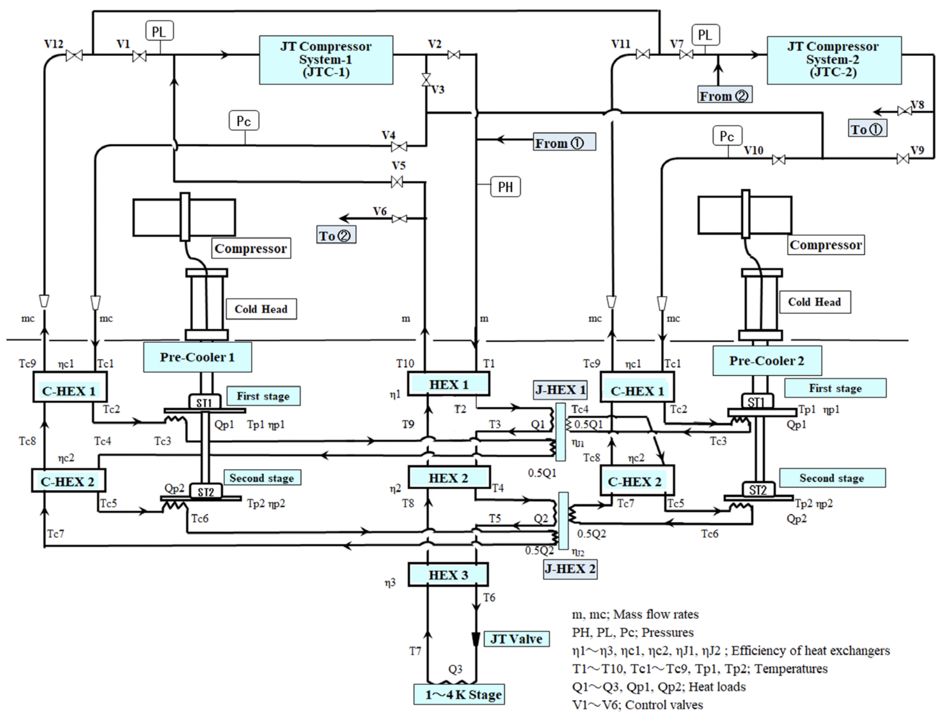

Figure 3. Type-2 flow diagram of the proposed refrigerant circulation systems.

Figure 3 is a Type 2 system flow diagram with the two added refrigerant circulation systems (RCSs) without a circulation pump, two pre-coolers, and a JT heat exchanger system with two JT compressor systems. In Figure 3, the 4K-JT cooler can be replaced by a 1K-JT cooler. The RCS comprises two sets of two-stage heat exchanger (C-HEX 1 and 2) and one set of two-stage heat exchanger (J-HEX 1 and 2). These three sets of two-stage heat exchangers and two pre-cooler can

Table 1. Comparison of SPICA original to two proposed types.

Components of 4K-JT system	SPICA Original in Fig. 1			Proposed Type-1 in Fig.2			Proposed Type-2 in Fig. 3		
	Number	Mass (kg)	Power (W)	Number	Mass (kg)	Power (W)	Number	Mass (kg)	Power (W)
Pre-cooler (2ST)	3	30	229.5	2	20	163	2	20	163
JT compressor system	2 sets	24	144	2 sets	24	144	2 sets	24	78
JT heat exchangers	2 sets	12	0	2 sets	12	0	1 set	6	0
Latch type magnetic valve	6	3	0	12	6	0	12	6	0
Pressure transducer	8	4.4	4	10	5.5	5	9	4.95	4.5
Circulation pump	0	0	0	2	7	6	0	0	0
Circulation heat exchangers	0	0	0	2 sets	8	0	2 sets	9	0
Driver of pre-cooler (2ST)	3	21	154.6	2	14	98.0	2	14	98.0
Driver of JT cooler (JTC)	2	22	85.3	2	22	86.3	2	22	63.4
Driver of circulation pump	0	0	0	2	0.4	24	0	0	0
Total		116.4	617.3		118.9	526.3		106.0	406.8

Components of 1K-JT system	SPICA Original in Fig. 1			Proposed Type-1 in Fig.2			Proposed Type-2 in Fig. 3		
	Number	Mass (kg)	Power (W)	Number	Mass (kg)	Power (W)	Number	Mass (kg)	Power (W)
Pre-cooler (2ST)	3	30	184.5	2	20	143	2	20	143
JT compressor system	2 sets	48	144	2 sets	48	144	2 sets	48	78
JT heat exchangers	2 sets	12	0	2 sets	12	0	1 set	6	0
Latch type magnetic valve	6	3	0	12	6	0	12	6	0
Pressure transducer	8	4.4	4	12	6.6	6	9	4.95	4.5
Circulation pump	0	0	0	2	7	6	0	0	0
Circulation heat exchangers	0	0	0	2 sets	8	0	2 sets	9	0
Driver of pre-cooler (2ST)	3	21	140.2	2	14	91.5	2	14	91.5
Driver of JT cooler (JTC)	4	44	124.0	4	44	126.0	4	44	106.6
Driver of circulation pump	0	0	0	2	0.4	24	0	0	0
Total		162.4	596.6		166.0	540.5		152.0	423.7

be connected by long stainless tubing with small diameters and thin walls to reduce heat conduction loss. The Type 2 system uses one JT compressor system to circulate the refrigerant instead of the circulation pump in Figure 2. Twelve latch-type solenoid valves and two pressure transducers are equipped when adding the RCS. In the Type 2 system, the working gas in the RCS and JT cooler, except the pre-cooler, must be the same.

Operational Description of Proposed Refrigerant Circulation System

Nominal operation of the Type 1 system is done independently with the 4K-JT cooler and refrigerant circulation system (RCS) with the latch type solenoid valves V3 and V6 closed. When a JT compressor system or a pre-cooler in a 4K-JT cooler has trouble, then the 4K-JT cooler is halted, then the normal 4K-JT cooler with a RCS is operated by itself with increased input power. When a circulation pump has trouble, the latch type solenoid valves V3 and V6 are opened. Then the normal circulation pump is operated alone for the two refrigerant circulation systems.

The JT compressor system 1 uses the 4K-JT cooler and JT compressor. System 2 uses the RCS. The nominal operation of the Type 2 system is for each pre-cooler and the RCS independently with latch-type solenoid valves V1, V3, V6, and V8 closed. If the JT compressor system 1 has trouble, then JT compressor system 2 is changed to use the 4K-JT cooler. One normal compressor of JT compressor system 1 is useful for the RCS with valves V2, V5, V7, and V9 closed. When one pre-cooler of two pre-coolers has trouble, then the troubled pre-cooler is stopped. The normal pre-cooler with an RCS is only operated with increased input power. In case the pre-cooler 1 has trouble, the latch type solenoid valves V4 and V12 are closed. If pre-cooler 2 has trouble, latch type solenoid valves V10 and V11 are closed.

COMPARISON WITH SPICA ORIGINAL AND PROPOSED TYPES

Table 1 presents a summary of comparison with the mass and power consumption of the 4K-JT system and 1K-JT system of SPICA originally in Figure 1 and proposed Type 1 and Type 2 in Figures 2 and 3.

The proposed Type 1 increases the mass 2.2% and decreases the power consumption 12.1% to the SPICA originally. The mass and the power consumption of the proposed Type 2 is decreased by 7.5% and 31.6% respectively to SPICA originally. The proposed Type 2 has a slightly more complicated configuration, but it presents important benefits in terms of its mass and power consumption.

Parasitic heat loss through the cylinder of our double-stage Stirling cooler (2ST) was measured. The parasitic heat loss was typically 800 mW at the 85 K first-stage temperature and 200 mW at the 19 K second-stage temperature. These numbers are comparable to the cooling capacity of the 2ST. Therefore, the present plan for the mechanical cooler system shown in Figure 1 uses three sets of 2ST for 4K-JT and 1K-JT coolers, respectively, for redundancy. When one 2ST presents difficulty and halts, one of two nominal 2STs must reject the parasitic heat loss, also one 2ST is used for the JT cooler as a pre-cooler. However, the proposed refrigerant circulation system uses only stainless tubing with small diameter and thin walls for thermal connection between the heat exchangers of JT cooler and the cold stages of the pre-cooler. Because the tubing can be long, the heat conduction loss can be of 1/100 to 1/1000 of the parasitic heat loss through the 2ST cylinder, which is a beneficial arrangement for the limitation of thermal links and decrease of the heat exchanger assemblies.

THERMAL BALANCE ANALYSIS OF REFRIGERANT CIRCULATION SYSTEM

Thermal design by heat balance analysis to attain optimum design of 4K-JT or 1K-JT cooler was investigated and presented in an earlier report[5].

As described herein, to attain optimum thermal design of refrigerant circulation systems (RCSs), heat balance analysis is conducted. For that analysis, the thermal cycle flow diagram presented in Figures 2 and 3 are divided into two sections, one shows the area around second-stage heat exchangers (C-HEX2, JHEX2) and the second stage of the pre-cooler and the other shows the area around first-stage heat exchangers (C-HEX1, J-HEX1) and the first stage of the pre-cooler

The working gas of refrigerant circulation systems are assumed to be the same as that in the JT cycle. It is defined as the mass flow rate (mc) and constant pressure (Pc).

Heat balance analysis around second-stage heat exchangers and the pre-cooler

The heat exchange capacity (Q2) of J-HEX2 and the heat exchange capacity (Qp2) at the second stage of the pre-cooler are given by the following equations.

$$Q2 = m\,(h_4 - h_5) = mc\,(h_{c7} - h_{c6}) \tag{1}$$

$$Qp2 = mc\,(h_{c5} - h_{c6}) \tag{2}$$

Heat exchange efficiency η_{J2} of the heat exchanger (C-HEX2) is expressed by enthalpy as shown below.

$$\eta_{c2} = (h_{c8} - h_{c7}) / (h_{c4} - h_{c7}) \tag{3}$$

From equation (3), h_{c8} is expressed as shown below.

$$h_{c8} = (1 - \eta_{c2})\,h_{c7} + \eta_{c2}\,h_{c4} \tag{3a}$$

Heat balance of the heat exchanger (C-HEX2) is expressed as

$$h_{c8} - h_{c7} = h_{c4} - h_{c5}\,. \tag{4}$$

From equation (3) and equation (4), h_{c5} is expressed as

$$h_{c5} = (1 - \eta_{c2})\,h_{c4} + \eta_{c2}\,h_{c7}\,. \tag{5}$$

Subtracting equation (1) from equation (2), the following equation is obtained.

$$Qp2 - Q2 = mc\,(h_{c5} - h_{c7}) \tag{6}$$

Substituting equation (5) into equation (6), one obtains the following equation.

$$Qp2 - Q2 = mc\,[(1 - \eta_{c2})\,h_{c4} - \eta_{c2}\,h_{c7}\,h_{c7}] = mc\,(1 - \eta_{c2})\,(h_{c4} - h_{c7}) \tag{7}$$

Heat balance analysis around first-stage heat exchangers and the pre-cooler

The heat exchange capacity (Q1) of J-HEX1 and the heat exchange capacity (Qp1) at the first stage of the pre-cooler are given by the following equations.

$$Q1 = m(h_2 - h_3) = mc\,(h_{c4} - h_{c3}) \tag{8}$$

$$Qp1 = mc\,(h_{c2} - h_{c3}) \tag{9}$$

Heat exchange efficiency η_{J1} of the heat exchanger (C-HEX1) is expressed by enthalpy as shown below.

$$\eta_{c1} = (h_{c9} - h_{c8}) / (h_{c1} - h_{c8}) \tag{10}$$

Heat balance of the heat exchanger (C-HEX1) is expressed as

$$h_{c9} - h_{c8} = h_{c1} - h_{c2} \tag{11}$$

From equation (10) and equation (11), h_{c2} is

$$h_{c2} = (1 - \eta_{c1})\, h_{c1} + \eta_{c1}\, h_{c8} \tag{12}$$

Subtracting equation (8) from equation (9) yields the following equation.

$$Qp1 - Q1 = mc\,(h_{c2} - h_{c4}) \tag{13}$$

Substituting equation (12) and equation (3a) into equation (13) produces the following.

$$Qp1 - Q1 = mc\,[(1 - \eta_{c1})\, h_{c1} + \eta_{c1}\,(1 - \eta_{c2})\, h_{c7} - (1 - \eta_{c1}\,\eta_{c2})\, h_{c4}] \tag{14}$$

Investigation of relational equations for h_{c4} and h_{c7}

Equation (7) and equation (14) are composed from enthalpy (h_{c1}), enthalpy (h_{c4}) and enthalpy (h_{c7}). Therein, enthalpy (h_{c1}) represents the circulating pressure (Pc) and supply inlet temperature (Tc1) of the heat exchanger (C-HEX1), which are given as initial analysis conditions.

Given that the working gas in the refrigerant circulation system and JT cooler except for the pre-cooler are the same, the heat exchange efficiency η_{J2} of the heat exchanger (J-HEX2) is expressed by enthalpy as shown below.

$$\eta_{J2} = (h_{c7} - h_{c6}) / (h_4 - h_{c6}) \tag{15}$$

From equation (15), equation (1) is expressed as three relations of Q2 shown below.

$$Q2 = m\,(h_4 - h_5) = mc\,(h_{c7} - h_{c6}) = mc\,\eta_{J2}\,(h_4 - h_{c6}) \tag{1a}$$

Eliminating h_4 and h_{c6} from the three relations to leave h_{c7} and h_5 for Q2 in equation (1a), h_{c7} yields the following expression.

$$h_{c7} = h_5 + Q2\,[1/m + (1 - 1/\eta_{J2})/mc] \tag{16}$$

Under the condition described above, heat exchange efficiency η_{J1} of the heat exchanger (J-HEX1) is also expressed by enthalpy as shown below.

$$\eta_{J1} = (h_{c4} - h_{c3}) / (h_2 - h_{c3}) \tag{17}$$

From equation (17), equation (8) is expressed as three relations of Q1 shown below.

$$Q1 = m\,(h_2 - h_3) = mc\,(h_{c4} - h_{c3}) = mc\,\eta_{J1}\,(h_2 - h_{c3}) \tag{8a}$$

Eliminating h_2 and h_{c3} from the three relations to leave h_{c4} and h_3 for Q1 in equation (8a), h_{c4} is expressed as presented below.

$$h_{c4} = h_3 + Q1\,[1/m + (1 - 1/\eta_{J1})/mc] \tag{18}$$

DEMONSTRATION OF THERMAL BALANCE ANALYSIS OF RCS

Demonstrations of heat balance analysis of RCS for the 4K-JT cooler and the 1K-JT cooler were performed.

Figure 4 shows the cooling capacities (Qp_1 and Qp_2) at each stage of the pre-cooler shown against the mass flow rate (mc) of the refrigerant circulation system with efficiency (η_{c1} and η_{c2}) of the refrigerant circulation exchangers (C-HEX 1 and 2) and efficiency (η_{J1} and η_{J2}) of the heat exchangers (J-HEX 1 and 2) as parameters. From experimental data obtained from the 4K-JT cooler lifetime test, the mass flow rate (m), temperatures (T_1, T_3, T_5, T_7), heat loads (Q1, Q2, Q3) of each stage, and JT supply pressure (PH) are fixed respectively as 2.43 NL/min (=7.24 gr/s), 293 K, 90 K, 18 K, 4.5 K, 250 mW, 150 mW, 40 mW, and 1.6 MPa for thermal balance analysis. Results presented in Figure 4 are calculated under the condition that the inlet temperature (Tc_1), the mass flow rate (mc), and pressure (Pc) in the refrigerant circulation system are selected respectively as 293 K, 2.43 NL/min, and 0.4 MPa.

Figure 5 presents the respective cooling capacities (Qp_1 and Qp_2) at each stage of the pre-cooler shown against the mass flow rate (mc) of the refrigerant circulation system with efficiency (η_{c1} and η_{c2}) of the refrigerant circulation exchangers (C-HEX 1 and 2) and efficiency (η_{J1} and η_{J2}) of the heat exchangers (J-HEX 1 and 2) as parameters. From our design data of the 1K-JT cooler, the mass flow rate (m), temperatures (T_1, T_3, T_5, T_7) and heat loads (Q1, Q2, Q3) of each stage, and JT supply

$\eta_{c1,2}$	$\eta_{J1,2}$	Qp1 (mW)	Qp2 (mW)
0.95	0.95	481.00	294.94
	0.9	482.01	294.64
0.96	0.96	433.49	265.99
	0.9	434.45	265.72
0.97	0.97	386.63	237.03
	0.9	387.47	236.79
0.98	0.98	340.44	208.04
	0.9	341.07	207.86
0.99	0.99	294.89	179.03
	0.9	295.24	178.93

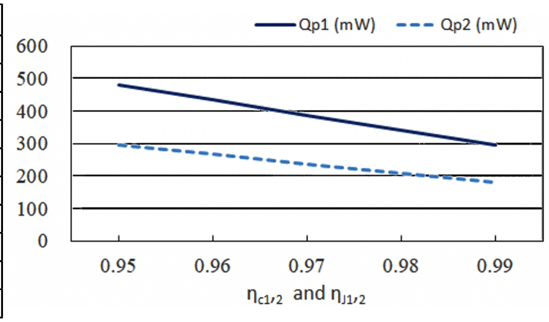

Figure 4. Demonstration analysis of RCS for the 4K-JT cooler.

$\eta_{c1,2}$	$\eta_{j1,2}$	Qp1 (mW)	Qp2 (mW)
0.95	0.95	212.47	140.68
	0.9	212.93	140.56
0.96	0.96	193.42	128.56
	0.9	193.86	128.45
0.97	0.97	174.65	116.43
	0.9	175.03	116.34
0.98	0.98	156.16	104.30
	0.9	156.45	104.22
0.99	0.99	137.94	92.15
	0.9	138.10	92.11

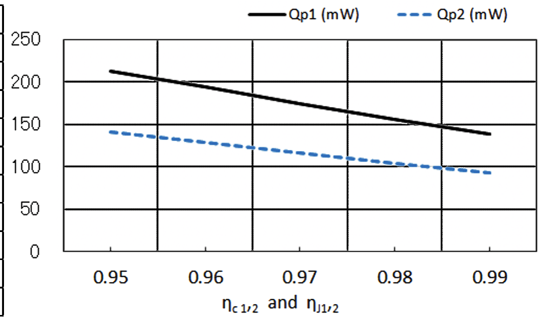

Figure 5. Demonstration analysis of RCS for the 1K-JT cooler.

pressure (PH) are fixed respectively as 1.0 NL/min (=2.23 gr/s), 293 K, 90 K, 15 K, 4.5 K, 120 mW, 80 mW, 10 mW and 0.7 MPa for thermal balance analysis. Results shown in Figure 5 are calculated under conditions in which the inlet temperature (Tc_1), the mass flow rate (mc), and pressure (Pc) in the refrigerant circulation system are selected respectively as 293 K, 1.0 NL/min, and 0.2 MPa.

Both Figures 4 and 5 show that the efficiency (η_{J1} and η_{J2}) of the heat exchangers (J-HEX 1 and 2) has no influence on cooling capacities (Qp_1 and Qp_2) at each stage of the pre-cooler. The efficiency (η_{c1} and η_{c2}) of the refrigerant circulation exchangers (C-HEX 1 and 2) must be greater than 98% to our 2ST as a pre-cooler.

CONCLUSIONS

This report has described a refrigerant circulation system (RCS) designed to improve the continuity of the SPICA cryogenic system cooling operations when the pre-cooler or JT cooler becomes troublesome or shows degraded performance. The added refrigerant circulation system enhances the redundancy and reliability of the SPICA cryogenic system. As additional effects, the number of pre-coolers and the power consumption are decreased. The arrangement limitations of the thermal link and heat exchanger assemblies are also decreased.

Investigation conducted using theoretical analyses based on enthalpy balance was conducted to elucidate aspects of the refrigerant circulation system. Relational expressions between the cooling capacities (Qp_1 and Qp_2) at each stage of the pre-cooler, the mass flow rate (m) of the JT cooler, and the mass flow rate (mc) of the refrigerant circulation system with the efficiency (η_{c1} and η_{c2}) of the refrigerant circulation exchangers (C-HEX 1 and 2) and the efficiency (η_{J1} and η_{J2}) of the heat exchangers (J-HEX 1 and 2) are introduced.

Results obtained from demonstrations of the RCS for the 4K-JT cooler and 1K-JT cooler show that the efficiency (η_{c1} and η_{c2}) of the refrigerant circulation exchangers (C-HEX 1 and 2) must be greater than 98% to our 2ST as a pre-cooler.

Refrigerant circulation systems (RCSs) are anticipated for use as a key cryogenic apparatus for use in future astronomy missions such as SPICA, with multi-cooling systems that include numerous mechanical coolers.

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