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Lunar nuclear power plant design for thermal-hydraulic cooling in nano-scale environment: Nuclear engineering-based interdisciplinary nanotechnology

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1. Introduction

The environment of the Moon is nearly vacant, which has very low density of several kinds of gases. It has the molecular level contents of the lunar atmosphere in Table 1, which is recognized that radiation heat transfer is a major cooling method [1]. The coolant of the nuclear power plant (NPP) in the lunar base is the Moon surface soil [2], which is known as the regolith. The regolith is the layer of loose and heterogeneous material covering the solid rock. For finding the optimized length of the radiator of the coolant in the lunar NPP, the produced power and Moon environmental temperature [3] are needed. This makes the particular heat transfer characteristics in heat transfer in the Moon surface. The radiation is the only heat transfer way due to very weak atmosphere. It is very cold in the night time and very hot in the daytime on the surface of the ground [4]. There are comparisons between lunar high land soil and Earth averages in Table 2.

In the historical consideration, Konstantin Tsiolkovsky made a suggestion for the colony on the Moon [5]. There are a number of ideas for the conceptual design which have been proposed by several scientists. In 1954, Arthur C. Clarke mentioned a lunar base of inflatable modules covered in lunar dust for insulation. John S. Rinehart suggested the structure of the stationary ocean of dust, because there could be a mile-deep dust ocean on the Moon [6], which gives a safer design. In 1959, the project horizon was launched regarding the U.S. Army's plan to establish a fort on the Moon by 1967 [7]. H. H. Koelle, a German rocket engineer of the Army Ballistic Missile Agency, leaded the project (ABMA). There was the first landing in 1965 and 245 tons of cargos were transported to the outpost by 1966.

2. Methods and Results

The numerical modeling is done in Fig. 1 for the loop of NPP with several assumptions. The heat transfer loop is connoted in the heat exchanger. There is a nodalization of heat exchanger in Fig. 2, where the nodals are from #1 to #9. It is necessary to fix the constant environmental temperature in Moon due to the big temperature difference between day time and night time. It is assumed that the maximum day time temperature is 396.15 *K* for the modeling. The regolith flow is shown in Fig. 3 and the nodalization of the flow is made in Fig. 4.

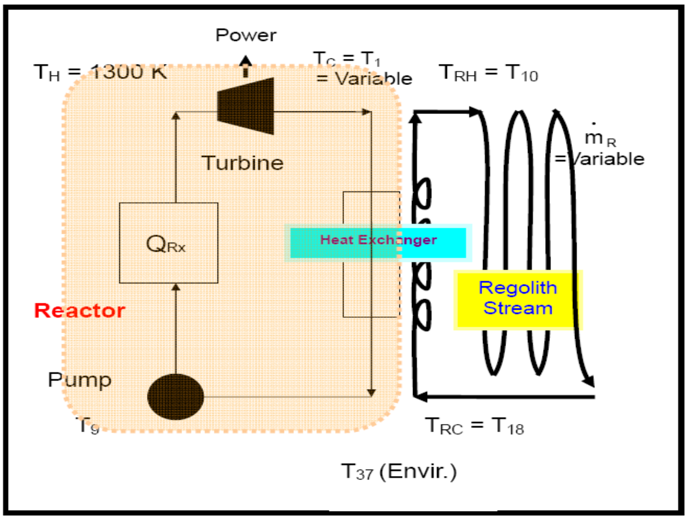

Fig. 1. Lunar nuclear power plant.

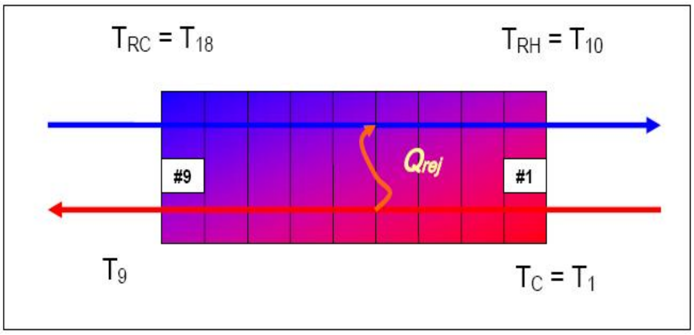

Fig. 2. Heat exchanger nodalization.

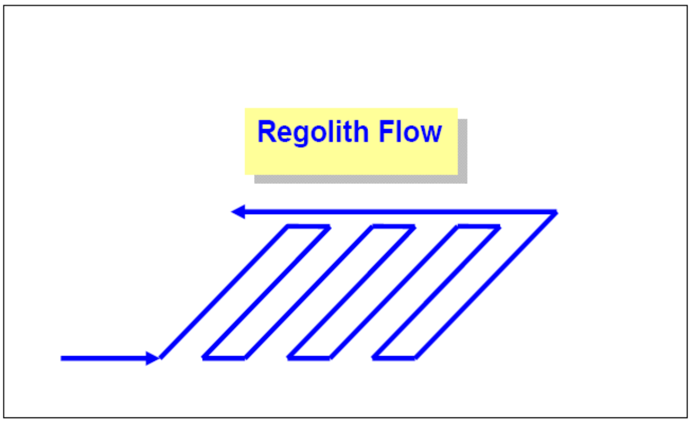

Fig. 3. Regolith flow.

The total nodal numbers are 20. The thermal energy from the heat exchanger is cooled by the ambient lunar environment. There is the rejected thermal energy from reactor in (1).

$$Q_{rej} = \left(1 - 0.6\left(\frac{T_H - T_C}{T_H}\right)\right) Q_{Rx} = \left(1 - 0.6\left(\frac{1300 - T_C}{1300}\right)\right) Q_{Rx} \qquad (1)$$

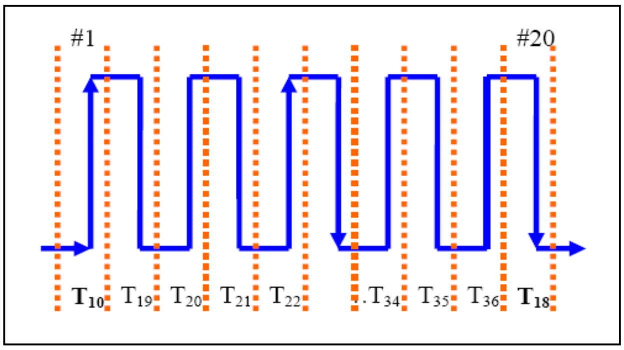

Fig. 4. Regolith flow nodalization.

The temperature of exit from turbine T_C is changed by the heat exchanger which is cooled subsequently by the regolith flow. There are 9 nodals in the heat exchanger. In the heat exchanger, the energy is transferred by radiation as $\varepsilon^{HX} = 1.0$.

$$Q_{nodal\#1}{}^{HX} = \sigma\varepsilon^{HX} A\left(T_1^4 - T_{10}^4\right) \qquad (2)$$

$$\begin{aligned} Q_{rej} &= Q_1{}^{HX} + Q_2{}^{HX} + Q_3{}^{HX} + Q_4{}^{HX} + Q_5{}^{HX} \\ &+ Q_6{}^{HX} + Q_7{}^{HX} + Q_8{}^{HX} + Q_9{}^{HX} \end{aligned} \qquad (3)$$

NTU (Number of Transfer Units) can show the length of the heat exchanger. This is modified as the radiation hear transfer (4) and (5). Mass flow rate ($\dot{m}$) is 15.1 *kg/s* and $C_p^{potassium}$ is 0.8 $kJ/(kg \cdot K)$ for potassium coolant flow in heat exchanger. It is shown that T_1 and T_9 should be same. T_1 (also T_9) is changed by the thermal efficiency.

$$Modified\ NTU = \frac{T_1 - T_{18}}{T_9{}^4 - T_{10}{}^4} = \frac{1260 - T_{RC}}{1260^4 - T_{RH}{}^4} \qquad (4)$$

$$HXLenght = \frac{\dot{m} C_p{}^{potassium}}{\sigma\,\varepsilon^{HX} P} \times Modified\ NTU \qquad (5)$$

The heat flux is done radiation from the regolith to the lunar environment. $Q_{nodal\#1}{}^{reg}$ is changeable by the distance of the regolith flow. Total nodals are 20 for the model. The regolith flow in radiator is in (6). The mass flow rate ($\dot{m}$) is obtained by ρVA of the regolith flow and the density is 0.3 kg/m^3. Otherwise, the velocity is variable. The area of the coolant is obtained by the heat conduction equation of (6) and the radiation heat transfer equation of (7). The area is calculated by iterations with the optimized regolith flow length. The nodal #1 has the rejected heat which is different from the rejected heat of the nodal #20 for the radiation heat transfer to environment. Temperature for T_{37} is 396.15 *K*. The rejected heat in each nodal is in (6). As a result, the T_{10} is calculated in equation (9).

$$Q_1{}^{reg} = \dot{m} C_p \left(T_{10} - T_{19}\right) \qquad (6)$$

$$\begin{aligned} Q_{rej} &= Q_1{}^{reg} + Q_2{}^{reg} + Q_3{}^{reg} + Q_4{}^{reg} + Q_5{}^{reg} \\ &+ \ldots + Q_{17}{}^{reg} + Q_{18}{}^{reg} + Q_{19}{}^{reg} + Q_{20}{}^{reg} \end{aligned} \qquad (7)$$

$$Q_1{}^{reg} = \sigma\,\varepsilon A\left(T_{10}^4 - T_{37}^4\right) = \sigma\,\varepsilon A\left(T_{10}^4 - (396.15)^4\right) \qquad (8)$$

$$T_{10} = \sqrt[4]{\frac{Q_1{}^{reg}}{\sigma\,\varepsilon A} + (396.15)^4} \qquad (9)$$

3. Conclusions

The coolant material of regolith in the Moon is optimized for the NPP. By the simulation, there are some results. Fig. 5 gives that the minimum length of the regolith stream is 6,100 *m* at the 0.204 *m* of diameter in the cylindrical shape condenser. In Fig. 6, the mass flow rate is changed by the nodal number. The heat exchanger nodalization with temperature is in Fig. 7. The thermal efficiency and T_C are changed by the regolith flow length in Fig. 8. The temperature is calculated as the 9 nodals by radiation heat transfer from the potassium coolant to the regolith flow.

The high efficiency is due to the lunar environment where the radiation is the only heat transfer to the environment and this efficiency could be changeable by the combination of the length and diameter of the regolith flow. This means the future lunar NPP with the high thermal efficiency could be a prospective engineering design, which is a different merit from the Earth condition. There are the comparisons of conduction, convection, and radiation heat transfers in Table 3 where the particular characteristics are described in the three cases [8]. The radiation depends on the surface area, which was explained above as the efficiency is related to the combination of the length and diameter of the regolith flow. Considering the nanoscopic view, Fig. 9 shows the comparisons of nanoscopic heat transfers in which the radiation heat transfer performs without any interaction with matter [9]. This is one of the reasons for the higher efficiency in the radiation heat transfer, because there is the negligible heating energy transfer to any substance in lunar atmosphere which is shown in Table 1. That is to say, the conduction and convection heat transfers in the lunar environment are nearly zero.

It is very important to keep the stability of the coolant in the lunar NPP addition to the economic factor. So, the optimized coolant loop length is a critical issue. Fig. 10 shows the meaning of the nuclear nanontechnology in the space development where the characteristics of this study are shown as the interdisciplinary matter incorporated with the molecular level property in lunar environment.

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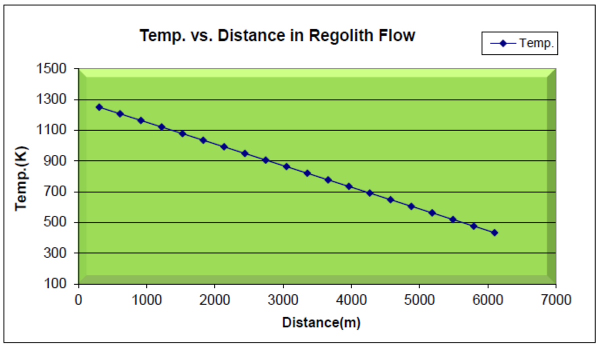


Fig. 5. Optimized energy rejection by radiation in regolith flow.

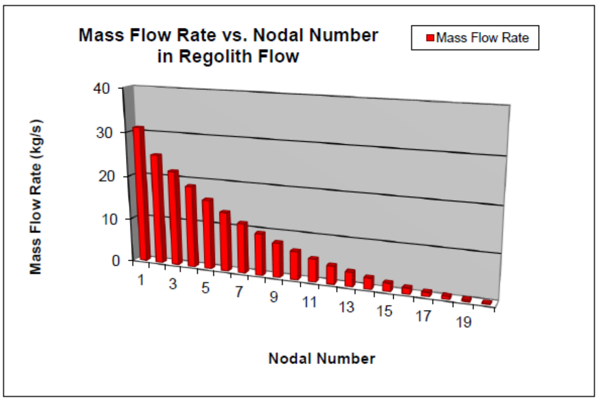


Fig. 6. Mass flow rate by the nodal number in regolith flow.

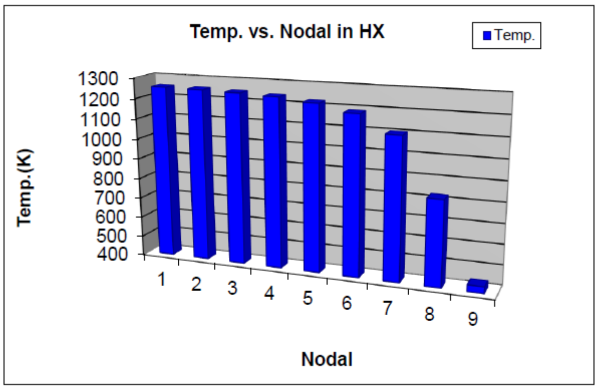


Fig. 7. Heat exchanger nodalization with temperature.

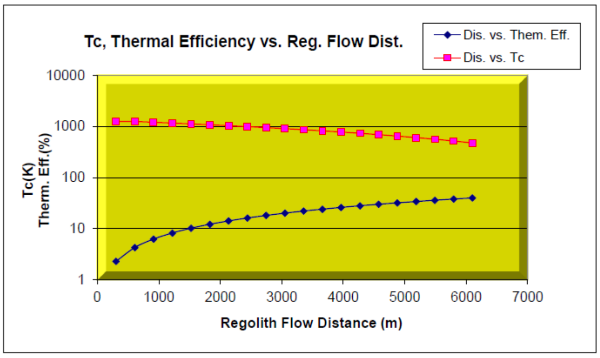
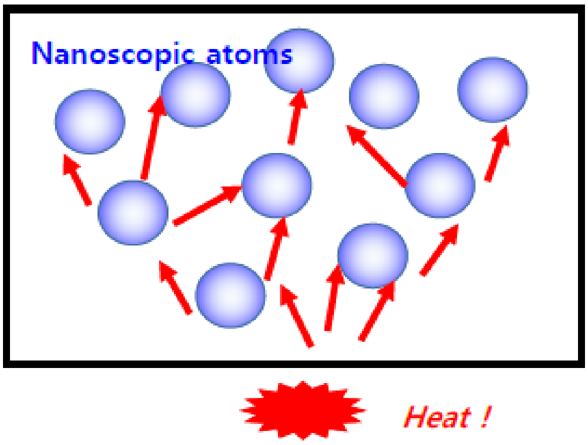
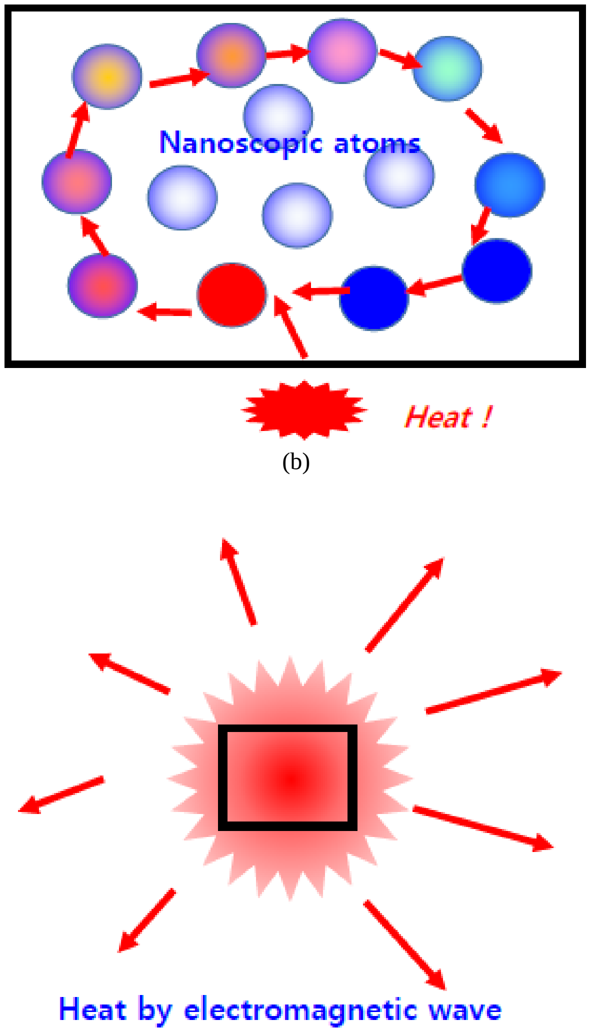


Fig. 8. T_C and Thermal efficiency following regolith flow distance.



(a)



(b)

(c)

Fig. 9. Comparisons of nanoscopic heat transfers, (a) Conduction, (b) Convection, and (c) Radiation.

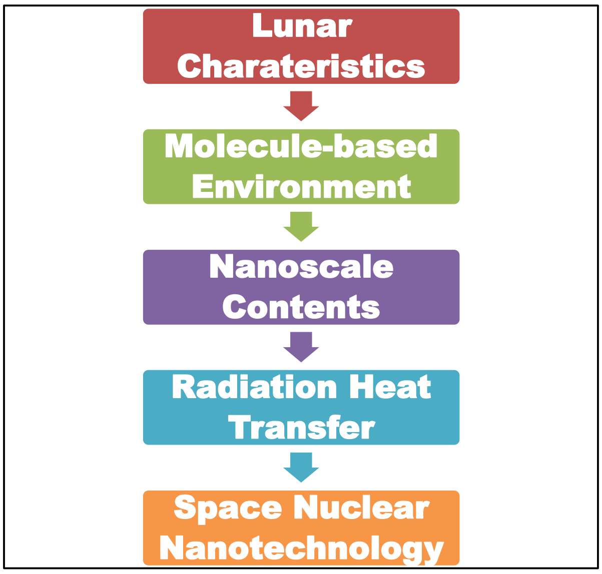


Fig. 10. Meaning of the nuclear nanontechnology in the space development.

Table I: Contents of lunar atmosphere

Element	*Quantity (element/cm^3)*
Argon	40,000
Helium	20,000 ~ 40,000
Sodium	70
Potassium	17
Hydrogen	17

Table II: Comparisons between averaged lunar high land and Earth soil in ppm

Element	*Lunar highland*	*Earth*
Oxygen	446,000	466,000
Silicon	210,000	277,000
Aluminum	133,000	81,300
Iron	48,700	50,000
Calcium	106,800	36,300
Sodium	3100	28,300
Potassium	800	25,900
Magnesium	45,500	20,900
Titanium	3100	4400
Hydrogen	56	1400
Phosphorous	500	1050
Manganese	675	950
Carbon	100	200
Chlorine	17	130
Chromium	850	100

Table III: Comparisons of conduction, convection, and radiation heat transfers

	Conduction	*Convection*	*Radiation*
Reason	Heat flow in material	Flowing fluid	Electromagnetic wave
Property	Thermal conductivity (λ)	Heat transfer coefficient (h)	Emissivity (ε)
Dependency	Thickness	Surface area	Surface area