An experimental study regarding the determination of seasonal heat transfer coefficient in KURT by convection conditions
An experimental study regarding the determination of seasonal heat transfer coefficient in KURT by convection conditions

Chanhoon Yoon\textsuperscript{a,}\textsuperscript{*}, Sangki Kwon\textsuperscript{b}, Jin Kim\textsuperscript{b}, Heuijoo Choi\textsuperscript{a}

\textsuperscript{a}Radioactive Waste Technology Development Division, Korea Atomic Energy Research Institute, Republic of Korea
\textsuperscript{b}Department of Energy Resources Engineering, Inha University, Incheon, Republic of Korea

\textbf{A R T I C L E I N F O}

\textbf{Article history:}
Received 29 September 2011
Received in revised form 19 June 2012
Accepted 29 June 2012
Available online 3 August 2012

\textbf{Keywords:}
High-level radioactive waste repository
KURT
Heat transfer coefficient
Natural convection
Forced convection

\textbf{A B S T R A C T}

In high-level radioactive waste repositories, heat is generated by the radioactive decay of the waste. This can affect the safety of the repository because the surrounding environment can be changed by heat transferred through the rock. Therefore, in order to ensure the safety of the repository, the temperature change of the atmosphere in the repository due to the heat generated by high-level radioactive wastes needs to be predicted and an appropriate heat reduction system is required. Through the construction of the KAERI Underground Research Tunnel (KURT) by Korea Atomic Energy Research Institute (KAERI), variable experiments about radioactive wastes disposal are in progress and the data on the properties of the surrounding rock in KURT had already been secured. As the internal heater section in KURT is heated by a heater that is 2 m in length and 5 kW in capacity it heats the inside of the rock in the research module by 90 °C, which is regarded as a similar environment to a disposal tunnel. In this study, the seasonal environmental factors (dry–wet-bulb temperature, rock surface temperature, altitude) under the natural and forced convection were measured at the heater section in KURT for the determination of heat transfer coefficient. The results showed that the heat transfer coefficients in the heater section had little seasonal difference. And the averages under natural convection and forced convection were determined 4.53 W/m² K and 7.46 W/m² K, respectively.

\textcopyright 2012 Elsevier Ltd. All rights reserved.

1. Introduction

In cases involving high-level radioactive waste repositories, disposal containers sealed at the bottom of disposal tunnels generate heat at around 100–150 °C depends on whether buffers are used or not for quite some time due to the radioactive decay of high level wastes after sealing. Heat transfer through rock, convection from rock surfaces and heat transfer due to groundwater inflows etc, serve great roles in atmospheric temperature rises in disposal tunnels (Kim and Kwon, 2005). These atmospheric temperature rises adversely affect waste transportation and storage, work environments in repositories and the safety of disposed high level wastes. After disposing the wastes in disposal holes with buffers, around 70% of normally generated heat should be removed through ventilation (Heath and Wilkins, 1999), and the ventilation rate from disposal tunnels should be adjustable in order to respond to demands from situations such as unexpected emergency states. That is, predicting atmospheric temperatures in environments surrounded by underground rock such as high-level radioactive waste repositories and controlling atmospheric environments in the repositories through suitable heat removal systems are very important. Environments in the repositories in underground rock are mainly determined by heat transfer through rock and spaces and the heat transfer is greatly affected by the thermal properties of rock and the atmosphere, the shapes of disposal spaces, season and whether groundwater surges out. Therefore, to predict atmospheric temperatures in the repositories, the thermal properties of underground rock such as heat conductivity, initial rock temperature, thermal diffusion, thermal gradient and viscosity should be calculated and the heat transfer coefficient should be determined through measurement of atmospheric environmental factors such as dry–wet-bulb temperatures and altitudes. Next, a computer numerical analysis processes should be implemented using the produced results. In addition, to determine the amount of heat reduction in atmosphere and waste of repository, numerical simulation using factors such as the thermal conduction, thermal convection, thermal radiation etc occurring in the rock including buffers in the surroundings are necessary. If atmospheric temperatures in the repositories are predicted and the amounts of heat reductions are calculated, the cooling time of the heat generated by the wastes will be determined and furthermore, it will be possible to establish appropriate heat removal systems (ventilation and cooling systems) to control atmospheric environments in the repositories.
2. Theory of heat transfer coefficient

To establish optimum ventilation systems of high-level radioactive waste repositories, not only the thermal properties of rock should be first calculated but also the atmospheric properties of the spaces surrounded by rock should be determined to apply the results as initial conditions of numerical simulation. Among key factors that determined the properties of the underground space atmosphere, heat transfer coefficient can be said to be a very important factor in predicting the atmospheric temperatures. The heat discharged by rock surfaces can be expressed by heat flux \( q \) which is determined by heat transfer coefficient and temperature difference between rock and atmosphere as shown in Eq. (1) McPherson, 1993.

\[
q = h(\theta_r - \theta_a) \quad (W/m^2)
\]

The total heat transfer coefficient \( h \) is composed of convective heat transfer coefficient \( h_c \) and radiative heat transfer coefficient \( h_r \) as shown in Eq. (2) and applicable theories and values vary with convection conditions (forced convection and natural convection). Where, \( a_b \) is absorption fraction that means the heat removed by the water, this showed values of around 0.3–0.4 on the results of measurement. Unlike the theory of convective heat transfer coefficient that vary with convection conditions, radiative heat transfer coefficient is determined by atmospheric temperatures as shown in Eq. (3). Radiative heat refers to radioactive heat transfer and the heat generated by the vibrations of atoms and the temperature is generally increased due to steam and carbon dioxide absorbing radiative heat while oxygen and nitrogen do not work the same Mills, 1995. \( \sigma \) refers to Stefan–Boltzmann constant applied to Stefan–Boltzmann law that indicates a values of 5.67 × 10^{-8} W/m^2 K^4 (ASHRAE, 1989). \( T_m \) refers to the average temperature between two points and in this study; this means the average dry-bulb temperature of the atmosphere in the heater section.

\[
h = h_c + a_b h_r \quad (W/m^2 K)
\]

\[
h_r = 4 \times \sigma \times T_m^3 \quad (W/m^2 K)
\]

The fraction of radiation absorbed \( a_b \), a constant to determine heat transfer coefficients can be expressed by Eq. (4) which is an empirical formula determined by curve fitting of data obtained through experiments.

\[
a_b = 0.104 \ln(147XL)
\]

where \( L \) is a Mean radiation path length normally determined as 3D. \( X \) is a Moisture content that indicates how many water particles are contained in the air. This is set forth under following equation:

\[
X = 0.622 \times \frac{e}{P - e \frac{kg}{M^2K}}
\]
Atmospheric pressure $P$ was obtained by measuring the altitudes changing over time and converting the results into atmospheric pressure. And, $e$ is actual water vapor pressure which is calculated using saturation vapor pressure as shown by following equation:

$$e = e_{sw} - AP\Delta T$$

(6)

where $A$ = Psychrometric constant (kPa/°C), $P$ = Barometric pressure (kPa), $\Delta T = T_d - T_w$ (°C), $e_{sw} = 610.6 \times 10^{-6} \exp \left( \frac{273.27}{T_d + 273.27} \right)$. $A$ in Eq. (6) is a Psychrometric constant that normally has a value of 0.000644 kPa/°C. $\Delta T$ shows the difference between the dry bulb temperature ($T_d$) and the wet bulb temperature ($T_w$).

2.1. Natural convection condition

In the case of natural convection condition since gas movements in repositories becomes extremely slow, a large part of heat transfer should be done by radiative heat transfer. However, it is also expected that the effect of the convective heat transfer arising from the heat generated by high level wastes should also be large. As shown in Eq. (7), convective heat transfer coefficient is determined by $Nu$ (Nusselt number) regardless of convection conditions.

$$h_c = \frac{Nu}{\ell} \left( W/m^2 K \right)$$

(7)

where $K_a$ = Thermal conductivity of air $(2.2348 \times 10^{-4} \, \text{W/m K})$, $\ell$ = Hydraulic mean dimeter $(m)$, $T$ = Absolute temperature $(K)$, $Nu$ is defined as the ratio of convective heat transfer to conduction heat transfer this is dimensionless numbers that indicate dimensionless temperature gradients. To determine $Nu$ in natural convection condition, it can be indicated as a function of $Re$ (Reynolds number) that shows heat transfer properties and $Pr$ (Prandtl number) that shows the ratio between the diffusion of the amount of movements and the diffusion of heat as shown in Eq. (8). In this case, the $Nu_{ref}$ value in this equation is 0.36(Churchill, 1983) which is a factor to determine $Nu$ in the case of horizontal cylindrical shapes such as tunnels (Incropera and DeWitt, 1996).

$$Nu = \left[ Nu_{ref} + R^2 l \left( \frac{\ell^2 + 2\ell}{300} \right)^{\frac{3}{2}} \right]^{\frac{1}{2}}$$

(8)

The $Re$ in Eq. (8) represents the multiplication of $Gr$ (Grashof number) that represents the buoyancy resulting from gas density difference and $Pr$ as shown in Eq. (9). Like $Re$ (Reynolds number) that serves the role of judging succession to turbulence in forced convection condition, $Gr$ serves the role in natural convection condition (Eq. (10)). $Pr$ is a dimensionless number that shows the degree of the diffusion of viscosity in relation to the thermal diffusion by the air that passes on rock surfaces and this normally has a value between 0.7 and 0.8 in the case of air or other gases (Monson and Young, 1998).

$$R = \frac{Gr}{Pr}$$

(9)

$$Gr = \frac{g\beta A T L^3}{v^2}$$

(10)

$\beta$ = Volume expansivity $(K^{-1})$, $\Delta T$ = Temperature difference between the hot surface and the bulk fluid $(K)$, $L$ = Characteristic length $(\pi D/2, m)$, $v$ = Kinematic viscosity $(m^2/s)$.

2.2. Forced convection condition

In case the ventilation system in the heater section in KURT is operated, it is expected that gas movements will show forced convection condition and thus a large part of heat transfer will be done by convective heat transfer but if the velocity of the blowing air into KURT is low, the effect of convective heat transfer should not be significantly different from the effect of radiant heat transfer. Although convective heat transfer coefficient in forced convection condition is also determined through Eq. (7) regardless of convection conditions, the equation to determine $Nu$ will vary with convection conditions. In the case of forced convection, since the convective heat transfer coefficient is determined by the thickness of the boundary layer, air velocity and the flow of the turbulence generated by friction between air and walls, $Nu$ is determined by the Nunner’s equation shown in Eq. (11) that includes coefficient $(f)$ and Reynolds numbers $(Re Nunner, 1956)$.

$$Nu = \frac{0.35Re}{1 + 1.592(15.217 Re^{0.8353} - 1)/Re^{1.725}}$$

(11)

The friction factor and Reynolds numbers included in Eq. (11) that show the roughness of walls in the heater section at KURT and the flow states of the atmosphere can be expressed by Eqs. (12) and (13) respectively.

$$f = \frac{1}{4[2\log_{10}(Re) + 1.14]^7}$$

(12)

$$Re = \frac{\rho \cdot v \cdot d}{\mu}$$

(13)

where $e$ refers to the height of roughness and $d$ refers to the hydraulic diameter. In this study, $e$ value was actually measured using a laser distance measuring instrument and a protractor and based on the results, the average value was determined to be around 0.775 m (Yoon et al., 2010). To calculate the Reynolds number, the air density was calculated through measuring the altitudes of the heater section changing over time and measured the air velocity in the heater section using hot wires. $\mu$ is inverse proportional to Reynolds numbers is called absolute viscosity or dynamic viscosity and Sutherland’s equation (Crane Company, 1988) in Eq. (14) was used to determine $\mu$.

$$\mu = \mu_0 \times \left( \frac{a}{b} \right) \times \left( \frac{T}{T_0} \right)^{\mu}$$

(14)

$a = 0.555 T_0 + C$, $b = 0.555 T + C$, $\mu$ = Dynamic viscosity in centipoises at input temperature (N s/m$^2$), $\mu_0$ = Reference dynamic viscosity in centipoises (N s/m$^2$), $T$ = Input temperature in degrees Rankine (°R), $T_0$ = Reference temperature in degrees Rankine (°R), $C$ = Sutherland’s constant, 120. Where 0.01827 N s/m$^2$ was applied to $\mu_0$ and 524.07 °R was applied to $T_0$ to determine absolute viscosity over time.

3. Method of research

3.1. Feature of KAERI Underground Research Tunnel (KURT)

Fig. 1 is a schematic diagram of KURT where this study was conducted. This is a laboratory built at the rear of the KAERI site and is located on crystalloid granite. As a non-radioactive facility, its tunnel section is 6 m × 6 m and it is composed of a 180 m long access tunnel of a 10% downward gradient and a 75 m long research module tunnel. The research module tunnel is divided into a left tunnel and a right tunnel excavated to be 30 m and 45 m long respectively and diverse field experiments related to thermal, hydraulic, dynamic, chemical and microbiological behaviors are being conducted here (Kwon and Cho, 2009).

The right side of the research module at KURT where the experiment was conducted is a borehole heater test (BHT) section
(hereinafter, ‘heater section’) in which a 2 m long 5 kW capacity heater on the rock wall heats the inside of the rock at 90 °C as shown in Fig. 2 and the wall in the heater section showed dry rock surface conditions (Fig. 3). The reason why the temperature of the heat source was set to 90 °C is that, if the temperature is over 100 °C, the water in the surroundings would be converted into steam creating complicated thermal–hydraulic–dynamic phenomena and would cause difficulties in the analysis of experimental results and the verification of modeling. In other words, heaters that are heated to 100 °C or more may vaporize water in underground rock mass and this phenomenon may become a cause to make the analysis of the results of in situ tests and computer modeling difficult. Therefore, in the case of scaled model tests, separate pressurizing devices are also made in order to prevent the aforementioned phenomenon.

Fig. 4 shows the entrance of KURT where a blowing fan and an exhausting fan are installed to provide a comfortable environment for workers and visitors. To form forced convection environments in the heater section, the blowing fan was operated but not the exhaust fan. The blowing fan has specifications including airflow of 3.17 m³/s and a pressure of 1.47 kPa and they supply fresh outside air to the inside of the heater section through metal spiral ducts.
this time, the velocity of the discharged airflow into the heater section through the duct outlet was measured to be around 6.5 m/s. To minimize the effects of changes in the environments outside the heater section, a blocking wall is installed as shown in Fig. 5.

3.2. Shape of heater section

Before measuring atmospheric environment factors, the shape of the heater section was measured using an infrared light distance measuring instrument (DISTO™ lite) for the temperature predicting computer simulations to be implemented later. For the realization an accurate shape, even the locations of ducts and the size and location of the entrance of heater section were measured. The section after reinforcement determined when KURT was designed was 6 m × 6 m in the width and height respectively, but, the results of the measurements, the width and height of the tunnel were measured to be around 6.8 m and 6.19 m respectively as shown in Fig. 6.

Where the width of the heater section is the width at the center of the tunnel and the height is the average value of the heights measured at 2 m intervals from the entrance to the face as shown in Fig. 7. The heater is installed on the left wall of the heater section and is located at around 2 m from the floor and around 4.8 m from the entrance (Fig. 7).

In addition, to calculate the friction factor (f) for determining heat transfer coefficients under forced convection conditions in accordance with Eq. (9), the instrument shown in Fig. 8a was made to measure the height of roughness (e) of the tunnel walls. Based on the measured e values, the shape of the heater section tunnel walls was illustrated in Fig. 8b.

3.3. Measurement of environmental factors

To determine heat transfer coefficient in the heater section, environmental factors such as dry–wet-bulb temperatures, altitudes, rock surface temperatures in the heater section are necessary. Therefore, in this study, the above mentioned environmental factors were measured at regular intervals and in the case of natural convection condition; the factors were measured from 10:00 AM to 5:00 PM at 30 min intervals. In the case of forced convection condition, the factors were measured from 11:00 AM to 5:00 PM at 30 min intervals considering fan operation time. Dry–wet-bulb temperatures were measured using a sling psychrometer which is model PS100F of ERTCO in the UK and the altitudes were measured using a Model T-5 altimeter of American Paulin System in the USA and then the air density was calculated. The rock surface temperatures were measured using an infrared light ray temperature measuring instrument (ST20-Pro) of Raytek in the USA that can measure temperatures in the range of −32–535 °C. In the case of forced convection condition, the average wind velocity in the heater section was additionally measured using a digital hot-wire and the result of the measurement showed an average value of 0.81 m/s.

4. Preliminary results

4.1. Results from the experiment

4.1.1. Natural convection condition

Environmental factor measurement in natural convection condition was conducted in August 2009 in the case of summer and in January 2010 in the case of winter. Both seasons showed serene weather during the field experiments. In the case of summer, the atmospheric temperature outside the KURT at 10:00 AM was around 23.84 °C and the humidity was shown to be around 70%. At 2:00 PM, the temperature and humidity were shown to be around 29.47 °C and around 53.15% respectively. In winter, at 10:00 AM, the temperature and humidity were shown to be around 6.5 °C and 58.6% respectively and at 2:00 PM, the temperature and humidity were shown to be around 8.8 °C and 52% respectively.

To determine absorption fraction, the dry–wet-bulb temperatures of the atmosphere in the heater section were measured and then the differences were calculated. The results are shown in Fig. 9. In the case of summer, the temperatures changed by around 2.53–2.97 °C and showed an average difference of 2.71 °C. In the case of winter, the temperatures changed by around 2.23–3.3 °C and showed an average difference of 2.86 °C. The reason why the
sizes of seasonal dry–wet-bulb temperature differences were shown to be relatively small is considered to be the fact that relatively constant relative humidity is maintained because of the lights and dehumidifiers existing in the heater section. The absorption fractions determined through the measured dry–wet-bulb temperature difference were similar at 0.36 and 0.37 in summer and winter respectively. The seasonal rock surface and atmospheric temperature changes in the heater section measured to determine convective heat transfer coefficient in natural convection condition are shown in Fig. 10. The summer average rock surface temperature was shown to be around 21.75 °C and the winter average rock surface temperature was shown to be around 21.39 °C and thus seasonal changes were not significant. However, the average temperatures of the atmosphere in the heater section were shown to be 20.37 °C in summer and 18.91 °C in winter thereby showing a seasonal difference of around 1.5 °C. This is caused by the difference of property between rock and the atmosphere.

4.1.2. Forced convection condition

Experiments to determine heat transfer coefficient in forced convection condition were conducted two times during August 27–28, 2009 (summer) and January 21–22, 2010 respectively by operating the ventilation fan at KURT to implement forced convection condition. The fan was started at 10:45 AM and stopped at 5:00 PM and environmental factors were measured for 6 h from 11:00 AM to 5:00 PM at intervals of 30 min. The outside air was supplied by blowing and the results of the measurement, the discharge wind velocity from the duct was around 6.5 m/s on average and the velocity of the atmosphere in the heater section was around 0.81 m/s on average. Although literature presents that, in forced convection condition, radiative heat transfer is negligible since the size of radiative heat transfer coefficient is much smaller compared to the size of convective heat transfer coefficient, in this experiment, convective heat transfer coefficient was expected to be small because the velocity of the atmosphere in the heater

![Fig. 8. Measurement of height of roughness.](image1)

![Fig. 9. Difference of dry and wet bulb temperature.](image2)

![Fig. 10. Seasonal temperature of rock surface and atmosphere in the heater section.](image3)

![Fig. 11. Difference of dry and wet bulb temperature.](image4)
section was quite low and thus radiative heat transfer coefficient was also calculated.

Fig. 11 shows dry–wet-bulb temperature differences for determining absorption fractions and summer dry–wet-bulb temperature differences changed by around 1.16–1.95 °C to show a difference of around 1.75 °C on the average. The absorption fraction determined through this process was around 0.38 which was higher than the result in natural convection condition by 0.01. In the case of winter, the dry–wet-bulb temperature differences changed by around 2.98–4.39 °C to show a difference of around 3.94 °C on the average and the absorption fraction was 0.31 which was a relatively low value.

As done with natural convection condition, the temperatures of rock surfaces were measured. In the case of summer, the temperatures gradually increased from around 22.3 °C to up to 22.9 °C due to the operation of fan, but no big differences over time occurred. However, in the case of winter, the temperatures decreased relatively more from around 21.7 °C to down to 19.8 °C. This is because the average temperature of the outside air flowed into the heater section was around 22.65 °C in summer and around 8.84 °C in winter. That is, the temperature difference between the rock in the heater section and the air outside KURT was greater in winter than in summer. In the case of summer, the average atmospheric temperature in the heater section was around 22.49 °C as the temperature gradually increased from 21.44 °C to up to 22.89 °C and in winter, the average atmospheric temperature was around 15.12 °C as the temperature decreased considerably from around 17.33 °C to down to 14.04 °C.

As mentioned in Section 2, methods to calculate convective heat transfer coefficient vary with convection conditions and in particular, the determination of Reynolds number is essential in forced convection condition. In the case of natural convection condition, while a factor that greatly affected determination of convective heat transfer coefficient was temperature difference between the rock surface and atmosphere, in the case of forced convection condition, changes in the dynamic viscosity, air density, changes in Reynolds number and roughness of the heater section due to the inflow air are important factors. That is, as certain amounts of air flow into the underground space, the air moves in lamina flows or turbulence flows to greatly affect the determination of heat transfer coefficient of the underground space. In this case, a factor that determines the form of the flows is Reynolds numbers. To determine Reynolds numbers, viscosity and air density should be calculated and the results are shown in Figs. 12 and 13 respectively.

The viscosity at an atmospheric temperature of 20 °C and under the standard atmospheric pressure condition is $1.82 \times 10^{-5}$ N s/m$^2$. In the case of summer, the determined viscosity was $1.85 \times 10^{-5}$ N s/m$^2$ on the average and thus an increase of around 0.03 from the state of the standard can be seen. It is considered that in summer, the viscosity of the atmosphere in the heater section increased due to the hot inflow air into the heater section from the outside. On the contrary, in winter, a decreasing tendency over time was shown and the determined viscosity coefficient was $1.81 \times 10^{-5}$ N s/m$^2$ on the average and thus a value decreased by around 0.01 compared to the standard atmospheric pressure condition was shown.

Fig. 13 shows air density which is inverse proportional to viscosity and its seasonal changes over time is illustrated. When the summer average atmospheric temperature was 22.49 °C, the average value of air density was shown to be 1.176 kg/m$^3$. Since the standard air density is 1.2 kg/m$^3$, it can be seen that the resultant value is smaller by around 0.024 kg/m$^3$. In the case of winter, while atmospheric temperature continuously decreased over time, air density continuously increased. When the average atmospheric temperature was 15.12 °C, the average air density was shown to be 1.206 kg/m$^3$ which was slightly higher than the standard air density. Using the viscosity and air density determined as such, Reynolds numbers are illustrated in Fig. 14.
The results of the illustration, Reynolds numbers show a form of almost the same as the tendency of changes in the air density in the heater section. This is because the values of viscosity are relatively much smaller than the air density values. In summer, the Reynolds numbers were shown to be 318,941 on the average while in winter they were shown to be 333,583 on the average. Given these values, it is considered that the atmosphere in the heater section shows a form of turbulence flows under forced convection regardless of seasons.

4.2. Determination of heat transfer coefficient

4.2.1. Natural convection

Based on the measurement of environmental factors of the heater section at KURT, the heat transfer coefficient was calculated in natural convection condition as shown in Fig. 15.

Seasonal radiative heat transfer coefficient showed results including a summer average of 5.74 W/m² K and a winter average of 5.65 W/m² K. Since radiative heat transfer coefficient increase as atmospheric temperatures increase, it can be seen that the radiative heat transfer coefficient in summer when the atmospheric temperatures were higher by around 1.46 °C were formed to be greater than those in winter. However, since the difference is a minute at 0.09 W/m² K on the average, it is considered that seasonal changes in radiative heat transfer coefficient are minor. Convective heat transfer coefficient in natural convection condition is mainly determined by temperature differences between rock surfaces and the atmosphere and the results of a calculation, the convective heat transfer coefficient in winter was shown to be 2.91 W/m² K on the average which was larger by around 0.5 than those in summer which was 2.41 W/m² K on the average. This is because the temperature differences between rock surfaces and the atmosphere were larger in winter by around 1.1 °C compared to summer. Given that the value of convective heat transfer coefficient was smaller to be around one half of the value of radiative heat transfer coefficient, it is considered that, even if heat sources would exist in the heater section at KURT, in natural convection condition, the effect of heat convection is smaller compared to the effect of heat radiation. However, if the temperature of heat sources is very high as with high level wastes, the effect of heat convection will greatly increase. To review changes in the total heat transfer coefficient based on the determined seasonal average radiative heat transfer coefficient and convective heat transfer coefficient, the tendency of changes in the total heat transfer coefficient showed similar to that of changes in convective heat transfer coefficient. This is because, the temperature of the atmosphere in the heater section are maintained to be relatively constant in natural convection conditions, and change of temperature difference between the rock surfaces and the atmosphere is greater than the change of atmospheric temperature difference. The results of a calculation of the total heat transfer coefficient, it showed 4.54 W/m² K in summer and 4.93 W/m² K in winter on average. Before this experiment was conducted, it was expected that, since temperature differences between the two seasons were considerable, a difference in the total heat transfer coefficient between the two seasons would greatly differ. However, as the difference is around 8% which are not considered to be large differences compared to atmospheric temperature differences between the two seasons. Given these results, it is considered that the total heat transfer coefficient of the heater section at KURT have relatively constant value in natural convection condition and that the value is 4.73 W/m² K on the average.

4.2.2. Forced convection

As with natural convection condition, changes in radiative and convective heat transfer coefficient of the heater section at KURT in forced convection condition are shown in Fig. 16. The results of a calculation of seasonal radiative heat transfer coefficient showed a summer average of 5.86 W/m² K and a winter average of 5.43 W/m² K and differences in radiative heat transfer coefficient between the two seasons are around five times larger than those in natural convection condition. This is because atmospheric temperatures in the heater section greatly increased or decreased due to the seasonal inflow air and the sizes of absorption fractions that work as a constant of radiative heat transfer coefficient show large differences with 0.38 in summer and 0.31 in winter.

Convective heat transfer coefficient in forced convection condition was calculated to be 5.43 W/m² K on average in summer and 5.54 W/m² K on average in winter. Smaller differences are shown compared to seasonal differences in radiative heat transfer coefficient because the outside air constantly supplied through blowing fans maintains the flow states of the atmosphere in the heater section to be constant. In other words, although temperature differences in rock surface and atmospheric between the seasons are larger compared to natural convection condition, the resultant sizes of convective heat transfer coefficient were shown to be similar between the seasons because the sizes of Reynolds numbers were similar. The total heat transfer coefficient was calculated
based on the two heat transfer coefficients and unlike the case of a natural convection condition, the results showed a tendency of variation similar to that of radiative heat transfer coefficient. As explained earlier, this is because, in a forced convection condition, while the atmosphere in the heater section showed large seasonal temperature differences and thus seasonal differences of radiative heat transfer coefficient were large, the Reynolds number was similar between the seasons and thus the differences of convective heat transfer coefficient were not shown to be big. Moreover, due to air velocity in the heater section was very low at 0.81 m/s in this experiment, the values of radiative heat transfer coefficient and absorption fractions played leading roles in determining the values of the total heat transfer coefficient. However, it is considered that, if the air velocity increases, the values of convective heat transfer coefficient will greatly increase and thus the roles of radiative heat transfer coefficient in determining the total heat transfer coefficient will become minor. The total heat transfer coefficient showed a difference of around 6% with a summer average of 7.68 W/m² K and a winter average of 7.24 W/m² K. However, as natural convection condition, given that climatic conditions in both seasons being opposite to each other, it is considered that the seasonal total heat transfer coefficient maintained relatively constant value and that the total heat transfer coefficient of the heater section at KURT under forced convection condition is 7.46 W/m² K on the average.

5. Conclusions

In this study, field experiments were conducted to determine heat transfer coefficient in the heater section in the KURT that has similar environments to the atmosphere in high-level radioactive waste repositories. The experiments were conducted in summer and winter and convection conditions were divided with whether ventilation fan was operated. Using dry–wet-bulb atmospheric temperatures, rock surface temperatures and altitudes obtained through the measurements, seasonal heat transfer coefficient was calculated by convection condition. The experimental results, the size of radiative heat transfer coefficient was greatly dependent on the temperatures of the atmosphere in the heater section regardless of convection conditions. In natural convection conditions, the size of convective heat transfer coefficient was mainly determined by temperature difference between rock surface and the atmosphere and in forced convection condition; those were determined by the size of the Reynolds number that was related to velocity of inflow air. Before the experiments, it was expected that the size of heat transfer coefficient would show a large difference between the seasons. However, only around 6–8% differences between the seasons occurred in the field experiments. Therefore, it is considered that the heat transfer coefficient of the heater section at KURT is maintained to be relatively constant regardless of seasons. The results of a calculation of heat transfer coefficient, the value was determined to be 4.73 W/m² K on the average in natural convection condition and 7.46 W/m² K on the average in forced convection condition. To make safe environments in high-level radioactive waste repository, atmospheric properties in the repositories such as heat transfer coefficient and the properties of surrounding rock should be carefully analyzed. Furthermore, it is considered that studies will be necessary in relation to the prediction of temperatures in the repositories through computerized numerical analysis processes.

Acknowledgements

This work has supported by Nuclear Research & Development program of the Korea Science and Engineering Foundation (KOSEF) through a grant funded by the Korean government (MEST). Also, this paper has supported by INHA University Research Grant.

References


