RESEARCH ON PERFORMANCE OF AIR-SOURCE HEAT PUMPS BASED ON THE TUNNEL AIR

Y.A. Li and W.G. Rong
Shandong Institute of Architecture and Engineering, Ji’nan, 250014, China

X.Y. Wang
Ji’nan University, Ji’nan, 250022, China

X.Q. Li
Shandong Institute of Architecture and Engineering, Ji’nan, 250014, China

(Received 28 March 2002; Accepted 17 July 2002)

ABSTRACT

This paper presents a new heat pump system in which tunnel air is served as air source. In this heat pump system, tunnel air acts as a heat source from which heat is extracted during heating, and as a heat sink to which heat is rejected during cooling. Coefficient of performance of the heat pump is always high because the temperature of tunnel air in summer is lower than that of atmosphere air, whereas that of tunnel air in winter is higher than that of atmosphere air.

Energy consumption of heat pumps in which atmosphere air and tunnel air is respectively served as source is compared and analyzed. Results show that tunnel air-source heat pump systems are energy efficient cooling/heating systems and the heating capacity of air-source heat pumps is free from drop in winter.

1. INTRODUCTION

Nowadays, air-source heat pumps find wide application in China because of improving of the people’s living standard. In general, an air-source heat pump consists of fan, filters, compressor, evaporator, condenser, short capillary tube, and controls. The apparatus for changing from cooling to heating or vice versa is often a reversing valve, in which the refrigerant flow to the condenser is changed to the evaporator. Alternatively, air passage through the condenser. An air-source heat pump system is composed of heat pumps and piping work. System components include heat exchangers, heat source, heat sink, and controls to provide effective and energy-efficient heating and cooling operations.

In an air-source heat pump system, outdoor air acts as a heat source from which heat is extracted during heating, and as a heat sink to which heat is rejected during cooling. Since outdoor air offers a universal heat-source, heat medium for the heat pump, air-source heat pumps are the most widely used heat pumps in residential and many commercial buildings [1,2].

The weakness of an air-source heat pump is that the heating capacity decreases when the outdoor temperature goes down.

2. ANALYSIS OF OUTDOOR AIR TEMPERATURE

It is vital that the outdoor air temperature is analyzed since the outdoor air temperature directly affects the performance of air-source heat pumps. The average outdoor air temperature in Jinan, Shandong Province, P.R. China, listed in Table 1 are based on detailed records from official weather stations of Shandong Weather Bureau, P.R. China [3].

Table 1 provides 10 year (1990-1999) average dry bulb temperature. There are 106 days in which the outdoor air temperature < 7°C and it accounts for 29% of total days in a year.

3. PERFORMANCE OF AIR-SOURCE HEAT PUMPS

The standard operation condition of the air-source heat pump in winter in China is that the outdoor air temperature is 7°C. In fact, the performance of air-source heat pumps varies with the outdoor air temperature, and so on. Fig. 1 is the performance curve of the air-source heat pump for the air to air heat pump in winter [2]. As shown in Fig. 1, the heat capacity of heat pump decreases when the outdoor air temperature falls in winter.
Table 1: Average temperature in Jinan

<table>
<thead>
<tr>
<th>Date</th>
<th>Temp. (°C)</th>
<th>Date</th>
<th>Temp. (°C)</th>
<th>Date</th>
<th>Temp. (°C)</th>
<th>Date</th>
<th>Temp. (°C)</th>
<th>Date</th>
<th>Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov.14</td>
<td>10.10</td>
<td>Dec.6</td>
<td>4.10</td>
<td>Dec.28</td>
<td>0.65</td>
<td>Jan.19</td>
<td>-1.13</td>
<td>Feb.10</td>
<td>2.83</td>
</tr>
<tr>
<td>Nov.15</td>
<td>8.23</td>
<td>Dec.7</td>
<td>3.38</td>
<td>Dec.29</td>
<td>1.75</td>
<td>Jan.20</td>
<td>-0.58</td>
<td>Feb.11</td>
<td>4.53</td>
</tr>
<tr>
<td>Nov.16</td>
<td>6.60</td>
<td>Dec.8</td>
<td>2.95</td>
<td>Dec.30</td>
<td>2.40</td>
<td>Jan.21</td>
<td>0.28</td>
<td>Feb.12</td>
<td>5.40</td>
</tr>
<tr>
<td>Nov.17</td>
<td>5.73</td>
<td>Dec.9</td>
<td>3.53</td>
<td>Dec.31</td>
<td>0.90</td>
<td>Jan.22</td>
<td>0.88</td>
<td>Feb.13</td>
<td>5.38</td>
</tr>
<tr>
<td>Nov.18</td>
<td>6.53</td>
<td>Dec.10</td>
<td>2.75</td>
<td>Jan.1</td>
<td>1.75</td>
<td>Jan.23</td>
<td>-0.50</td>
<td>Feb.14</td>
<td>4.85</td>
</tr>
<tr>
<td>Nov.19</td>
<td>5.83</td>
<td>Dec.11</td>
<td>1.78</td>
<td>Jan.2</td>
<td>2.68</td>
<td>Jan.24</td>
<td>-0.03</td>
<td>Feb.15</td>
<td>3.70</td>
</tr>
<tr>
<td>Nov.20</td>
<td>4.88</td>
<td>Dec.12</td>
<td>3.63</td>
<td>Jan.3</td>
<td>0.70</td>
<td>Jan.25</td>
<td>1.10</td>
<td>Feb.16</td>
<td>2.90</td>
</tr>
<tr>
<td>Nov.21</td>
<td>6.10</td>
<td>Dec.13</td>
<td>4.13</td>
<td>Jan.4</td>
<td>0.00</td>
<td>Jan.26</td>
<td>1.58</td>
<td>Feb.17</td>
<td>4.25</td>
</tr>
<tr>
<td>Nov.22</td>
<td>6.68</td>
<td>Dec.14</td>
<td>3.05</td>
<td>Jan.5</td>
<td>0.78</td>
<td>Jan.27</td>
<td>1.18</td>
<td>Feb.18</td>
<td>2.95</td>
</tr>
<tr>
<td>Nov.23</td>
<td>5.70</td>
<td>Dec.15</td>
<td>3.35</td>
<td>Jan.6</td>
<td>0.55</td>
<td>Jan.28</td>
<td>1.58</td>
<td>Feb.19</td>
<td>2.28</td>
</tr>
<tr>
<td>Nov.24</td>
<td>6.13</td>
<td>Dec.16</td>
<td>2.35</td>
<td>Jan.7</td>
<td>-0.80</td>
<td>Jan.29</td>
<td>1.43</td>
<td>Feb.20</td>
<td>2.58</td>
</tr>
<tr>
<td>Nov.25</td>
<td>5.35</td>
<td>Dec.17</td>
<td>1.98</td>
<td>Jan.8</td>
<td>-0.40</td>
<td>Jan.30</td>
<td>1.00</td>
<td>Feb.21</td>
<td>3.10</td>
</tr>
<tr>
<td>Nov.26</td>
<td>5.43</td>
<td>Dec.18</td>
<td>2.88</td>
<td>Jan.9</td>
<td>-0.20</td>
<td>Jan.31</td>
<td>-0.13</td>
<td>Feb.22</td>
<td>3.75</td>
</tr>
<tr>
<td>Nov.27</td>
<td>5.43</td>
<td>Dec.19</td>
<td>2.55</td>
<td>Jan.10</td>
<td>-0.13</td>
<td>Feb.1</td>
<td>-0.43</td>
<td>Feb.23</td>
<td>3.05</td>
</tr>
<tr>
<td>Nov.28</td>
<td>5.95</td>
<td>Dec.20</td>
<td>1.68</td>
<td>Jan.11</td>
<td>-0.45</td>
<td>Feb.2</td>
<td>-0.38</td>
<td>Feb.24</td>
<td>4.60</td>
</tr>
<tr>
<td>Nov.29</td>
<td>6.18</td>
<td>Dec.21</td>
<td>1.33</td>
<td>Jan.12</td>
<td>-0.28</td>
<td>Feb.3</td>
<td>-0.63</td>
<td>Feb.25</td>
<td>5.73</td>
</tr>
<tr>
<td>Nov.30</td>
<td>5.20</td>
<td>Dec.22</td>
<td>1.43</td>
<td>Jan.13</td>
<td>-0.58</td>
<td>Feb.4</td>
<td>1.43</td>
<td>Feb.26</td>
<td>6.83</td>
</tr>
<tr>
<td>Dec.1</td>
<td>2.60</td>
<td>Dec.23</td>
<td>2.03</td>
<td>Jan.14</td>
<td>-1.45</td>
<td>Feb.5</td>
<td>4.05</td>
<td>Feb.27</td>
<td>5.88</td>
</tr>
<tr>
<td>Dec.2</td>
<td>2.00</td>
<td>Dec.24</td>
<td>2.58</td>
<td>Jan.15</td>
<td>-0.38</td>
<td>Feb.6</td>
<td>4.23</td>
<td>Feb.28</td>
<td>4.73</td>
</tr>
<tr>
<td>Dec.3</td>
<td>2.65</td>
<td>Dec.25</td>
<td>2.48</td>
<td>Jan.16</td>
<td>-0.08</td>
<td>Feb.7</td>
<td>3.33</td>
<td>Mar.1</td>
<td>5.88</td>
</tr>
<tr>
<td>Dec.4</td>
<td>4.45</td>
<td>Dec.26</td>
<td>2.05</td>
<td>Jan.17</td>
<td>-0.98</td>
<td>Feb.8</td>
<td>2.28</td>
<td>Mar.2</td>
<td>7.15</td>
</tr>
<tr>
<td>Dec.5</td>
<td>3.58</td>
<td>Dec.27</td>
<td>1.53</td>
<td>Jan.18</td>
<td>-1.73</td>
<td>Feb.9</td>
<td>2.55</td>
<td>Mar.3</td>
<td>8.03</td>
</tr>
</tbody>
</table>

Fig. 1: Performance curve of the heat pump

When the air-source heat pump is operated in heating mode, a fall of the outdoor temperature causes a decrease in the evaporating temperature. A lower evaporating temperature results in increasing work done and increasing compression ratio so that volumetric efficiency of the air-source heat pump is decreased, a lower volumetric efficiency, a slightly refrigeration effect and a lower density of suction vapor. All these effects result in a smaller heating capacity of heat pump. The fall of the outdoor temperature also causes a rise in space heating load [4]. The intersection of the heating capacity curve and the heating coil load curve, at point o is the balance point at which the heating capacity of the heat pump is equal to the required heating coil load. When the outdoor temperature drops below this balance point, as shown in Fig. 2, supplementary heating from the electric or other heat source is required to maintain a preset discharge air temperature. Consequently, the system of heat pump has a low usage factor [5].

4. HEAT PUMP IN WHICH AIR IN TUNNEL IS SERVED AS SOURCE

Results of research show that the change of both the outdoor air temperature and the earth’s surface temperature is periodic [6]. In Fig. 2, temperature change curves of different depth stratum in the city P.R. China are shown. But there are only measured temperature data of stratum 3.2 m and above. It is should calculated to get temperature data of stratum under 3.2 m.
The earth’s crust is considered as the semi-infinite solid, and the differential equation for the temperature distribution is:

\[
\frac{\partial \theta}{\partial \tau} = a \frac{\partial^2 \theta}{\partial y^2} \tag{1}
\]

The boundary condition is:

\[
\theta_{p,\tau} = A_d \cos \frac{2\pi}{Z} \tau \tag{2}
\]

This is a problem which may be solved. The solution is given as:

\[
\theta_{y,\tau} = A_d e^{-\gamma} \cos \left( \frac{2\pi}{Z} \tau - \frac{\pi}{aZ} \right) \tag{3}
\]

Equation (3) will be written as with \( \Omega = \frac{2\pi}{Z} \) in Eq.(3):

\[
\theta_{y,\tau} = A_d e^{-\gamma} \cos \left( \Omega \tau - \frac{\Omega}{2a} \right) \tag{4}
\]

We have \( \theta_{y,\tau} = t_{y,\tau} - t_d \), so the temperature of different depths stratum is determined from Eq.(4) as:

\[
t_{y,\tau} = t_d + A_d e^{-\gamma} \cos \left( \Omega \tau - \frac{\Omega}{2a} \right) \tag{5}
\]

There is a tunnel under the earth’s surface in Jinan, Shandong Province, P.R. China. The aim to build the tunnel is to protect air-raid when it was built in 1960s. Length of the tunnel is about 993.5 m and depth of the tunnel center point is 6 m. Section of the tunnel takes shape of Roman arch and the area of cross-section is 4.037 m². Inner layer is limestone. There is general soil around the tunnel. Density of soil is 2000 kgm⁻³, coefficient of thermal conductivity is 1.6 wm⁻¹ oC⁻¹ [6]. The location of point O, point A and point B are shown in Fig. 3.

The air temperature of point O, point A and point B is measured in February because in that time the temperature of air can present that of air in winter in the tunnel due to postponing of temperature wave, and the data is listed in Table 2.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Parameter</th>
<th>Date</th>
<th>Date</th>
<th>Date</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>14/15</td>
<td>15/16</td>
<td>21/22</td>
<td>22/23</td>
</tr>
<tr>
<td>Outdoor point O</td>
<td>Dry bulb temp.</td>
<td>0.5</td>
<td>8.5</td>
<td>-2.3</td>
<td>-3.0</td>
</tr>
<tr>
<td></td>
<td>Wet bulb temp.</td>
<td>-2.3</td>
<td>3.6</td>
<td>-3.0</td>
<td>-3.5</td>
</tr>
<tr>
<td>In tunnel point A</td>
<td>Dry bulb temp.</td>
<td>4.5</td>
<td>10</td>
<td>1.6</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td>Wet bulb temp.</td>
<td>0</td>
<td>4.0</td>
<td>-0.8</td>
<td>0.1</td>
</tr>
<tr>
<td>In tunnel point B</td>
<td>Dry bulb temp.</td>
<td>12.6</td>
<td>13.1</td>
<td>9.9</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>Wet bulb temp.</td>
<td>5.9</td>
<td>6.0</td>
<td>5.0</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Fig. 3: Diagram of measured point seat
Table 2 showed that the average dry bulb temperature of outdoor is 0.9°C, the dry bulb temperature in tunnel is 8.1°C; the average wet bulb temperature of outdoor is -1.3°C, and the wet bulb temperature in tunnel is 3.2°C.

Fig. 4 showed that COP of heat pump in which outdoor air is served as source is 2.5, COP of heat pump in which air in tunnel is served as source is 3.3. COP of heat pump in which air in tunnel is served as source has greatly increased and result of energy conservation is very notable [7]. More important is in the absence of supplementary source in this heat pump system.

The heat pump in which air in tunnel is served as source will be used, only there is a tunnel. If there were no tunnels, there would be no tunnel air source heat pump systems. There were a lot of tunnels during the 1960s ~ 1970s in China, and but now there are a few tunnels in China. However air in caves is also served as the air-source heat pump source.

The teahouse locates in Jinan, the capital of East China’s Shandong Province, and space of it is 80 m². The heat pump in which tunnel air is served as air source, KFR-75, is installed in the teahouse, and it operates 872 hours in winter and the operating cost is only RMB 825 yuan; while for the heat pump in which indoor air is served as air source, KFR-75, the operating cost is RMB 1100 yuan in winter. From this example, we can see that the effect of energy conservation is remarkable if the tunnel air is served as the source of heat pump.

5. CONCLUSIONS

- Average dry bulb temperature in tunnel is 7°C higher than that in outdoor in winter in Jinan, Shandong Province, P.R. China.
- Heat capacity that tunnel air source heat pump generates can meet the needs of buildings in winter, and supplementary source can be eliminated.
- COP of heat pump in which air in tunnel is served as source in Jinan, P.R. China, is about 30% higher than that of outdoor air in winter (Feb.), and operating costs of this heat pump systems may be greatly decreased.
- Air in the tunnel, cave, underground, air-raid shelter and others can be served as the air-source heat pump source.

NOMENCLATURE

\[A_d\] amplitude of temperature in the earth’s surface, °C

\[a\] thermal diffusivity, \(a = \frac{\lambda}{\rho C}\), m²s⁻¹

\[C\] specific heat, kJkg⁻¹°C⁻¹

\[\tau_{\eta,\tau}\] temperature of different depth stratum, °C

\[t_{\eta(1)}\] average temperature of the earth’s surface in January, °C

\[t_{\eta(7)}\] average temperature of the earth’s surface in July, °C

\[t_d\] average temperature of the earth’s surface in a year, \(t_d = \frac{[t_{\eta(1)}+t_{\eta(7)}]}{2}\), °C

\[y\] depth of stratum, m

\[Z\] period of temperature’s wave, h

\[\rho\] density, kgm⁻³

\[\lambda\] thermal conductivity, wm⁻¹°C⁻¹

\[\Omega\] frequency of temperature’s wave

\[\tau\] time, h, \(\tau = 1, 2, 3, \ldots\)

\[\theta_{\eta,\tau}\] temperature difference, \(\theta_{\eta,\tau} = t_{\eta,\tau} - t_d\), °C

REFERENCES