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PREHEATING AND COOLING OF THE INCOMING AIR OF DWELLINGS USING AN EARTH-LAID PIPE

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Synopsis

The present work is an investigation of ground heat exchangers for the air-conditioning of the supply air to residential buildings. To this end, an analytical approximate solution for the temperature field of the ground in which a ground pipe has been laid is derived. This analytical approximate solution is applicable to a free-lying ground heat exchanger consisting of a single ground pipe. Extensions of this solution enable calculations for ground heat exchangers which are laid around a house, or which consist of several ground pipes connected in parallel.

The analytical approximate solutions form the basis for the derivation of basic principles for the design of ground heat exchangers. The freely-variable parameters which have the greatest influence on the heat output of the ground heat exchanger are the depth of installation and the length of the ground pipe.

As far as the maximisation of the annual heating and cooling yield of the ground heat exchanger is concerned, there exists an optimum installation depth which is determined by the thermal properties of the ground. The length of the ground heat exchanger is determined by the requirement that the air supply temperature at the end of the ground pipe must always exceed 0°C, even when the outdoor air temperature is extremely low. This prevents possible icing-up of the subsequent plate heat exchanger on the exhaust side.

The theoretical investigations are completed by measurements made during one year on a ground heat exchanger installed at a single-family dwelling.

List of symbols

a, a_E	[m²/s]	thermal diffusivity
B_0	[m]	influence breadth
$c_{p,L}$	[kJ/(kg*K)]	specific heat capacity of the air at constant pressure
d_R	[m]	diameter of the ground pipe
k_1	[W/(m*K)]	overall heat transfer coefficient of the ground pipe per unit of length
k_{KW}	[W/(m²*K)]	overall heat transfer coefficient of the cellar wall
$\dot{Q}_{EWT}$	[W]	heating or cooling power of the ground pipe
R_0	[m]	radius of the ground pipe
S_0	[m]	installation depth of the ground pipe
t	[s]	time
t_0	[s]	periodic time
$\dot{V}, \dot{V}_L$	[m³/s]	volume flow of air
x	[m]	course
y	[m]	course
Δz	[m]	unit of length
α	[W/(m²*K)]	convective heat transfer coefficient of the ground pipe
ϑ_A	[°C]	outdoor air temperature
ϑ_E	[°C]	earth temperature
$\vartheta_{E,a}$	[°C]	non-stationary component of the earth temperature

$\vartheta_{E,m}$	[°C]	stationary component of the earth temperature
$\vartheta_{E,O}$	[°C]	temperature at the surface of the earth
$\vartheta_{E,O,m}$	[°C]	stationary component of the temperature at the surface of the earth
$\vartheta_{E,R}$	[°C]	temperature at the surface of the pipe
$\vartheta_{E,R,a}$	[°C]	non-stationary component of the temperature at the surface of the pipe
$\vartheta_{E,R,m}$	[°C]	stationary component of the temperature at the surface of the pipe
ϑ_{Erd}	[°C]	temperature of the earth without ground pipe
$\Delta\vartheta_{Erd}$	[°C]	change of the temperature of the earth without ground pipe
ϑ_{K}	[°C]	temperature of the cellar
ϑ_{L}	[°C]	air temperature
$\vartheta_{L,R,A}$	[°C]	air temperature at the beginning of the ground pipe
$\vartheta_{L,R,E}$	[°C]	air temperature at the end of the ground pipe
ϑ_{m}	[°C]	mean value of the outdoor air temperature
ϑ_{max}	[°C]	maximum value of the outdoor air temperature
ϑ_{W}	[°C]	temperature of the cellar wall
λ_{E}	[W/(m*K)]	thermal conductivity of the earth
ρ_{L}	[kg/m^3]	density of the air

Introduction

In today's low-energy houses, the high degree of thermal insulation has reduced the transmitted heat requirement of buildings to such an extent that the ventilation heat requirement is becoming increasingly significant.

An important step in reducing ventilation heat losses is the installation of mechanical ventilation with heat recovery. The heat recovery unit consists of a plate heat exchanger, an air/air small heat pump or, as described in /1/, a plate heat exchanger followed by an air/air small heat pump.

A further method of reducing ventilation heat losses is the installation of a ground heat exchanger. In winter, the thermal energy stored in the ground is thus employed for pre-heating the outdoor air. This thermal energy is provided entirely by stored solar energy, since in the upper levels of the earth the geothermal heat flux is insignificant. According to Eckert /2/, this can be neglected down to a depth of 100 m. Schick /3/ indicates a value of 1.5 μcal/(cm^2*sec) (= 0.063 W/m^2) for the mean specific geothermal heat flux in the upper layers of the earth. Erdösi /4/ gives a value of 0.025 - 0.084 W/m^2 for this heat flux. In contrast, the mean annual value of the average radiation density of sunlight in the western Länder of the Federal Republic of Germany is 114 W/m^2 /5/.

The introduction of a ground heat exchanger improves not only the heat yield but also the operational reliability of the heat-recovery unit described above. In winter, outdoor temperatures significantly lower than 0°C result in icing of the plate heat exchanger on the exhaust side. When a suitably-dimensioned ground heat exchanger is introduced, the supply air temperature in the plate heat exchanger is never less than 0°C, even when the outdoor air temperature is extremely low. Icing of the plate heat exchanger is thus prevented. Furthermore, the raised supply air temperature results in shortened thaw times in the evaporator of the air/air heat pump.

In summer, the low earth temperature is used for partial cooling of the outdoor air. Since the temperature falls below the dew point at the walls of the ground pipe, condensation results, which partially dries the outdoor air. This process is not to be underestimated from the point of view of comfort, since supply air which is cooler and drier than the outdoor air is subjectively very pleasant in summer. The expressions "partial cooling" and "partial drying" emphasise that the cooling and drying capacities of the ground heat exchanger are smaller than those of conventional air-conditioning equipment, and that it is in no way possible to achieve a defined indoor climate with the aid of the ground heat exchanger alone.

Theoretical Principles

In order to design ground heat exchangers in the simplest possible way, an analytical solution of the ground temperature field for the case of a pipe laid in the ground is derived. Use is made of published partial solutions. Krischer /6/ first made use of the heat-source method and of conformal mapping in order to derive the following equation for the stationary-state ground temperature field of a pipe laid in the ground.

$$\vartheta_E(x,y) = \vartheta_{E,O} - \left(\vartheta_{E,R} - \vartheta_{E,O}\right) \cdot \frac{\ln\left(\frac{r_1}{r_2}\right)}{\ln\left(\frac{S_0}{R_0} + \sqrt{\left(\frac{S_0}{R_0}\right)^2 - 1}\right)}$$

$$\text{where: } r_1 = \sqrt{\left(x - \sqrt{S_0^2 - R_0^2}\right)^2 + y^2} \quad ;$$

$$r_2 = \sqrt{\left(x + \sqrt{S_0^2 - R_0^2}\right)^2 + y^2} \qquad (1)$$

The consideration of the monthly mean outdoor temperature reveals that the annual temperature variation, as seen in Fig. 1, is very well represented by a cosine oscillation of the form

$$\vartheta_L = \vartheta_m + (\vartheta_{max} - \vartheta_m) \cdot \cos\left(2\pi \frac{t}{t_0}\right) \qquad (2)$$

For this boundary condition, Grigull and Sandner /7/ made use of the Laplace transformation of the steady state (periodic steady state) to derive a solution for the one-dimensional, non-stationary differential equation for the ground in the absence of the pipe. The assumption of an infinitely large heat interface at the surface of the earth, which is justifiable according to von Cube /8/, results in simplification to

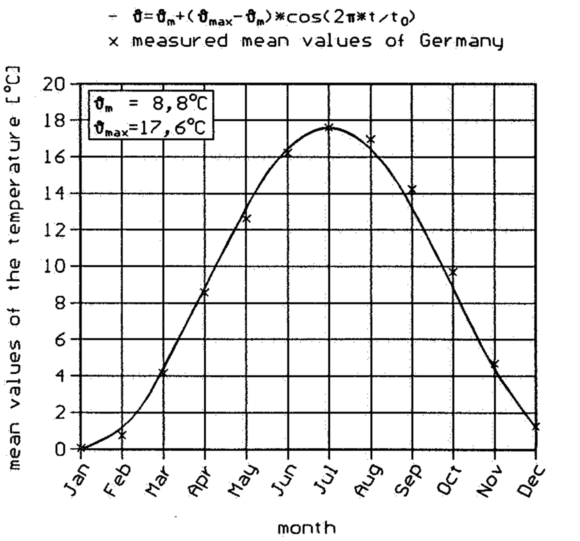

Fig. 1 Course of the outdoor temperature

$$\vartheta_E(x,t) = \vartheta_m + (\vartheta_{max} - \vartheta_m) \cdot e^{-\xi} \cdot \cos(p \cdot t - \xi)$$

$$\text{where:} \quad p = \frac{2\pi}{t_0} \quad ; \quad \xi = x \cdot \sqrt{\frac{\pi}{a \cdot t_0}} \qquad (3)$$

Since the differential equation for thermal conduction is a linear, partial differential equation, the superposition principle may be employed. This states that partial solutions of linear, ordinary or partial differential equations may be added.

On the basis of this superposition principle, the following equation is derived in /9/ with the aid of equations 1 and 3 for the non-stationary ground temperature field in the presence of a pipe laid in the ground.

$$\vartheta_E(x,y,t) = \vartheta_{E,O,m} - \left(\vartheta_{E,R,m} - \vartheta_{E,O,m}\right) \cdot \frac{\ln\left(\frac{r_1}{r_2}\right)}{\ln\left(\frac{S_0}{R_0} + \sqrt{\left(\frac{S_0}{R_0}\right)^2 - 1}\right)} +$$

$$+ (\vartheta_{max} - \vartheta_m) \cdot e^{-\xi} \cdot \cos(p \cdot t - \xi)$$

$$:= \vartheta_{E,m} + \vartheta_{E,a}$$

$$\text{where:}\ p = \frac{2\pi}{t_0} \quad ; \quad \xi = x \cdot \sqrt{\frac{\pi}{a \cdot t_0}} \quad ;$$

$$r_1 = \sqrt{\left(x - \sqrt{S_0^2 - R_0^2}\right)^2 + y^2} \quad ;$$

$$r_2 = \sqrt{\left(x + \sqrt{S_0^2 - R_0^2}\right)^2 + y^2} \quad ; \quad \vartheta_{E,O,m} \equiv \vartheta_m \qquad (4)$$

The stationary component of the temperature in the ground at the ground pipe $\vartheta_{E,R,m}$ is then

$$\vartheta_{E,R,m} = \frac{k^* \cdot \vartheta_{E,O,m} + \vartheta_{L,R} - \vartheta_{E,R,a}}{k^* + 1}$$

$$\text{where:} \quad k^* = 2\pi \frac{\lambda_E}{k_1} \cdot \frac{1}{\ln\left(\frac{S_0}{R_0} + \sqrt{\left(\frac{S_0}{R_0}\right)^2 - 1}\right)} \tag{5}$$

The thermal balance for a pipe element of length Δz yields the following equation for the air temperature at the end of the pipe element /9/:

$$\vartheta_{L,R,E} = \frac{\rho_L \cdot \dot{V} \cdot c_{p,L} \cdot \vartheta_{L,R,A} + \Delta z \cdot k_1 \cdot \left(\vartheta_{E,R} - \frac{1}{2} \cdot \vartheta_{L,R,A}\right)}{\rho_L \cdot \dot{V} \cdot c_{p,L} + \frac{1}{2} \Delta z \cdot k_1} \tag{6}$$

The temperature of the earth at the pipe $\vartheta_{E,R}$ is calculated here as follows:

$$\vartheta_{E,R} = \frac{k^* \cdot \vartheta_{Erd,R} + \vartheta_{L,R}}{k^* + 1}$$

$$\text{where:} \quad k^* = 2\pi \frac{\lambda_E}{k_1} \cdot \frac{1}{\ln\left(\frac{S_0}{R_0} + \sqrt{\left(\frac{S_0}{R_0}\right)^2 - 1}\right)} \tag{7}$$

The air temperature which results at the end of a ground pipe of length l is found by $(1/\Delta z)$fold application of Equation 6. The sensible heat yield or cooling effect of the ground pipe is given by

$$\dot{Q}_{EWT} = \rho_L \cdot \dot{V} \cdot c_{p,L} \cdot \left(\vartheta_{L,R,E} - \vartheta_{L,R,A}\right) \tag{8}$$

If, in summer, the temperature in the pipe falls below the dew-point, resulting in the condensation of water-vapour, the total (sensible + latent) cooling output of the ground pipe is given by the difference in enthalpy of the air before and after the ground pipe. The absolute air humidity at the end of the ground pipe is calculated from the water balance of the ground pipe with the aid of the analogy between heat and mass exchange /10/.

The temperatures $\vartheta_{E,R,m}$ (Eqn. 5) and $\vartheta_{E,R}$ (Eqn. 6) have the character of stationary temperatures, even though they are calculated from two non-stationary temperatures. The reason is that, according to the differential equation for the non-stationary temperature field, non-stationary temperatures are a function only of the thermal diffusivity but not of the thermal conductivity. These equations are therefore described as an approximate solution. In the present case, in which monthly mean values of temperature are considered, the temperature changes are small and the time intervals are large, so that the approximate solution is an excellent one.

Fig. 2 shows the earth temperature field which, according to Eqn. 4, results in winter (month: January) at the centre of a 42 m long ground pipe laid at a depth of 3 m. Average values for western Germany of earth parameters and of the course of the outdoor temperature were employed. The volume flow was 140 m^3/h. Inspection of the temperature field near to the ground pipe and consideration of the fact that, according to Ottel /11/,

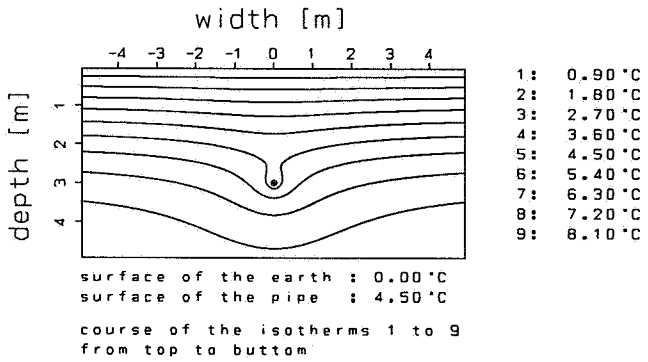

Fig. 2 Earth temperature field

the temperature in the ground at a distance of 2 m from the house is 2-3 K higher than that of the unperturbed ground reveal that the capacities of ground heat exchangers laid around the house are strongly influenced by the house itself.

In order to include the influence of the cellar wall in the analytical approximate solution, the following equation for the temperature increase $\Delta\vartheta_{Erd}$ of the unperturbed ground at a distance y_W from the cellar wall is derived in /9/.

$$\Delta\vartheta_{Erd} = (\vartheta_W - \vartheta_{Erd}) \cdot e^{-\xi_W}$$

$$\text{where: } \xi_W = y_W \cdot \sqrt{\frac{\pi}{a \cdot t_0}} \qquad (9)$$

The temperature at the outer face of the cellar wall ϑ_W is calculated from the 1-dimensional energy balance of the cellar wall, and is:

$$\vartheta_W = \frac{\vartheta_K + k_K^* \cdot \vartheta_{Erd}}{1 + k_K^*}$$

$$\text{where: } k_K^* = \frac{\lambda_E}{k_{KW}} \cdot \sqrt{\frac{\pi}{a \cdot t_0}} \qquad (9a)$$

ϑ_K is here the room temperature of the cellar and k_{KW} is the overall heat transfer coefficient of the cellar wall.

If, in Eqn. 7 for the calculation of the ground temperature at the ground pipe $\vartheta_{E,R}$, the temperature of the unperturbed ground $\vartheta_{Erd,R}$ is replaced by the new 'unperturbed' ground temperature $\vartheta_{Erd,R,n} = \vartheta_{Erd,R} + \Delta\vartheta_{Erd}$, the influence of the cellar wall is now taken into account.

If, for the ventilation of buildings larger than single-family dwellings, the ground heat exchanger is planned to consist of not one, but of many ground pipes connected in parallel, so-called pipe banks, it must be taken into consideration that the heat output of the individual ground pipes is influenced by their relative positions. In order to determine this influence, /9/ introduces the so-called influence breadth B_0, for which the following relationship is derived. B_0 is here made dimensionless relative to the depth of the ground pipe S_0.

$$B_0^* = \frac{B_0}{S_0} = \frac{2\pi}{\ln\left(S_0^* + \sqrt{S_0^{*2} - 1}\right)}$$

$$\text{where:} \quad S_0^* = \frac{S_0}{R_0} \qquad (10)$$

Eqn. 10 is evaluated graphically in Fig. 3. The ratio of the actual pipe separation to the influence breadth B_0 is a measure of the reduction of the heat and cooling output of the individual pipe in the bank relative to that of the free-lying single ground pipe. This provides a resource with whose aid the analytical approximate solution for the single ground pipe forms the basis for the approximate calculation of the heat

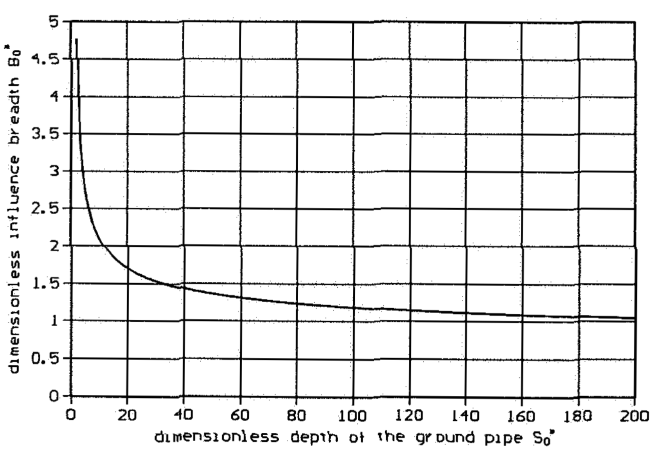

Fig. 3 Course of the dimensionless influence breadth

and cooling output of an entire pipe bank, without the necessity of performing an involved numerical calculation of the ground temperature field.

Experimental results

The ground heat exchanger under investigation was built for a single-family house and is shown schematically in Fig. 4. The ground heat exchanger is 42 m in length and is 125 mm in diameter. The outdoor air is propelled through the ground pipe by means of a tube fan with a measured power requirement of 50 W. The volume flow is 140 m^3/h.

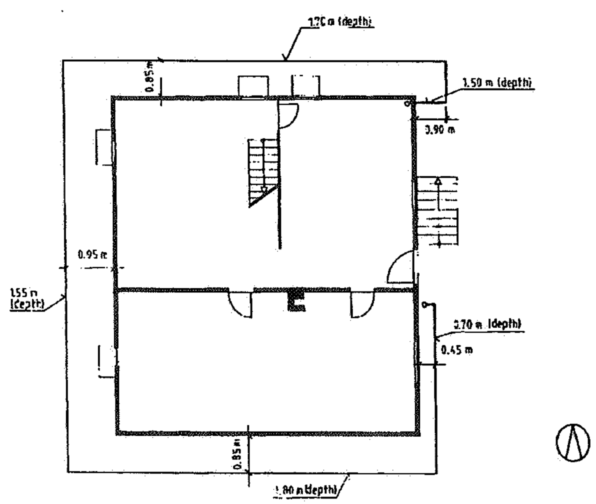

Fig. 4 Scheme of the ground heat exchanger

During the summer of 1990 under investigation, the ground heat exchanger provided partially cooled air during the months from May to Oktober. For these months, the experimentally determined monthly mean outdoor air temperatures are plotted in Fig. 5. Since no 20-year mean values exist for the location of the ex-

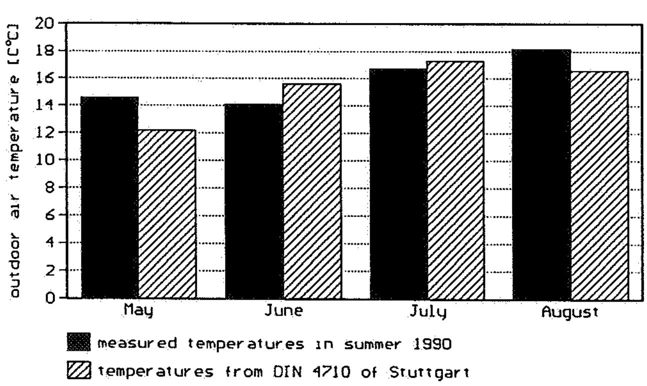

Fig. 5 Outdoor air temperatures

periment, the 20-year mean values from DIN 4710 /12/ of the air temperature at the location of the meteorological station at Stuttgart are plotted. Even though the 20-year mean values of the air temperature at the location of the ground heat exchanger will differ from those at Stuttgart, it is still possible to make the location independent statement that, in summer 1990, the months May and August were significantly warmer than the long-term mean temperatures.

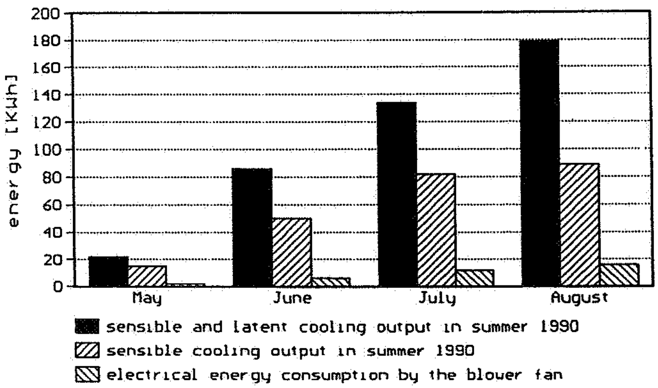

Fig. 6 Cooling output of the ground heat exchanger

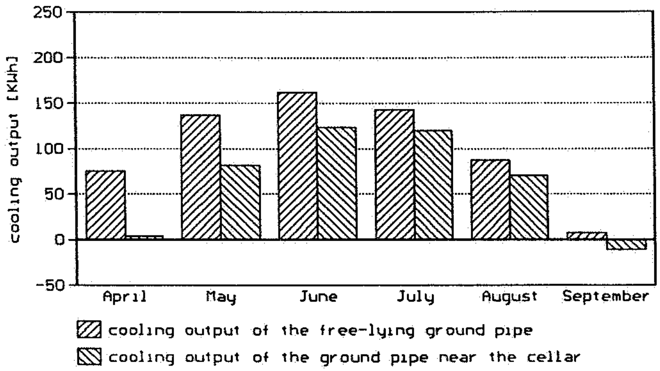

Fig. 7 Cooling output of the ground heat exchanger

Fig. 6 shows the cooling yield achieved in the individual months. A distinction is made here between the sensible and the total (sensible and latent) cooling yield. For the purposes of energetic evaluation, the electrical energy consumed by the blower fan whilst cooling the air is also plotted. During the entire summer of 1990, the ground heat exchanger provided 236 kWh of sensible cooling, or 421 kWh of sensible and latent cooling, whereby 36 kWh of electrical energy had to be supplied. The calculation of a coefficient of performance for the ground heat exchanger analogous to that for a heat-pump cycle yields a value of 6.6 in terms of the sensible cooling yield, and a value of 11.7 in terms of the total (sensible and latent) cooling yield.

Fig. 7 shows the mean cooling yield during the summer months to be expected of the ground heat exchanger under investigation. A negative cooling yield represents a heat yield. Alongside the cooling yield calculated from the analytical approximate solution (left-hand bars), the cooling yield under consideration of the cellar wall according to Eqn. 9 is also indicated (right-hand bars). The influence of the cellar wall upon the cooling yield of the ground heat exchanger becomes apparent in this diagram. Since the cellar wall is warmer than the ground, a nearby ground pipe suffers a significantly reduced cooling yield.

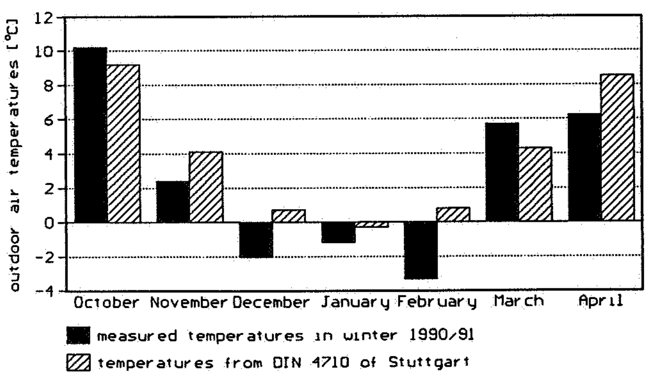

Fig. 8 Outdoor air temperatures

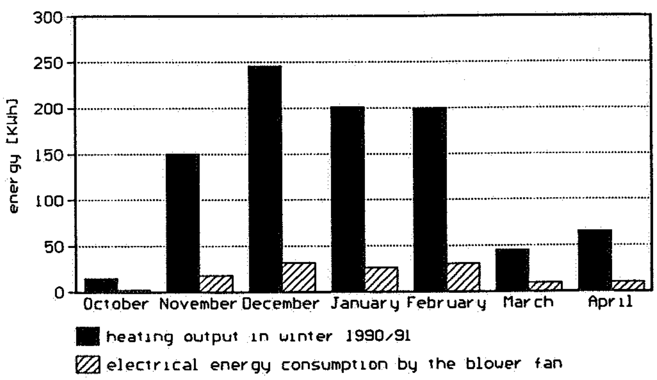

Fig. 9 Heating output of the ground heat exchanger

During the winter of 1990/91 under investigation, the ground heat exchanger provided prewarmed supply air during the months from October to April. Fig. 8 shows the mean monthly values of the outdoor air temperature for these months, alongside the 20-year mean values from DIN 4710 for Stuttgart. This diagram leads to the qualitative conclusion that the months from November to February were significantly colder than the long-term mean temperatures.

The heat yield achieved during the individual months is seen in Fig. 9. The electrical energy expended in the operation of the blower fan is plotted in addition. During the entire winter 1990/91, the ground heat exchanger provided 923 kWh of heat, for which 127 kWh of electrical energy had to be expended. The ground heat exchanger therefore has a coefficient of performance of 7.3 in terms of the heat yielded.

Fig. 10 shows the mean heat yield to be expected during the winter months. Alongside the heat yield which is calculated from the analytical approximate solution (left-hand bars), the heat yield under consideration of the cellar wall according to Eqn. 9 (right hand bars) is also plotted, analogous to the representation of the summer data. The influence of the cellar wall becomes apparent here: the heat quantity is significantly increased. The excess of heat over that provided by a free-lying ground heat exchanger can not, as described in /9/, be described as a supplementary heat yield, since this heat quantity results from a higher loss of heat from the cellar. The installation of the ground heat exchanger around the house therefore provides no energetic advantages.

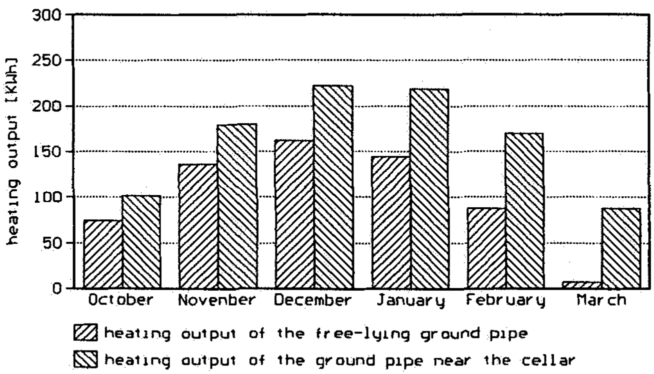

Fig. 10 Heating output of the ground heat exchanger

Design of ground heat exchangers

Many parameters which influence the heat or cooling output of the ground heat exchanger are predetermined by the position, the size and the use of the dwelling for which the ground heat exchanger is planned. These parameters are the thermal diffusivity and the thermal conductivity of the earth, the course of the outdoor temperature, and the volume of supply air. The only freely variable parameters which significantly influence the heat or cooling output are the depth and the length of the ground heat exchanger.

Figs. 11 and 12 show the mean expected annual heating and cooling yields of the ground heat exchanger investigated as a function of the installation depth, as calculated from the analytical approximate solution. It is apparent from these diagrams that an optimum installation depth exists at which the heating and cooling yields are maximised. This depth is 4.5 m in the present case. The optimum installation depth is dependent upon the thermal properties of the ground, as shown in /9/.

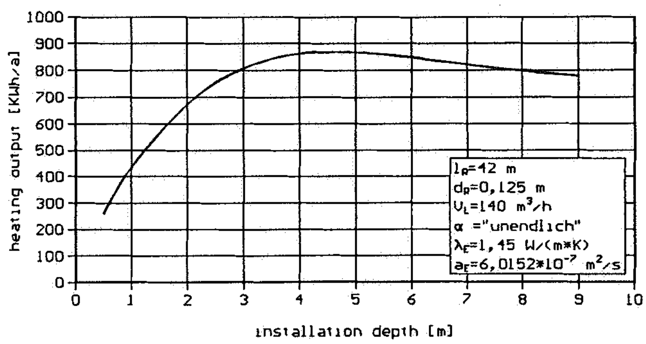

Fig. 11 Heating output of the ground heat exchanger

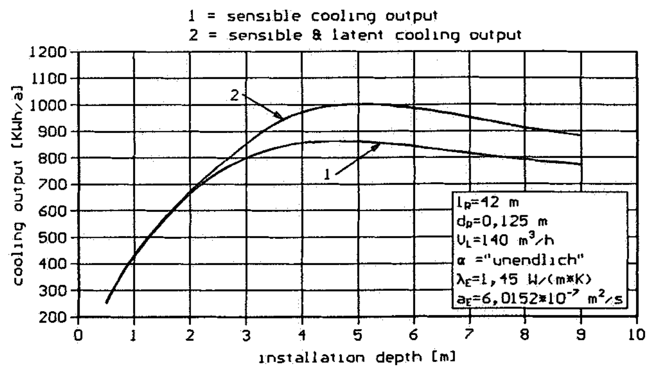

Fig. 12 Cooling output of the ground heat exchanger

The optimum pipe length is determined by the requirement that in winter, even in the case of short-period low-temperature extremes, the supply air temperature behind the ground pipe must always be greater than 0°C. This requirement is of great importance for the operation of the heat-recovery equipment.

Supply air temperatures below 0°C would result in icing of the exhaust air side within the plate heat exchanger of the heat-recovery equipment, which would seriously disrupt the function of the air-conditioning system.

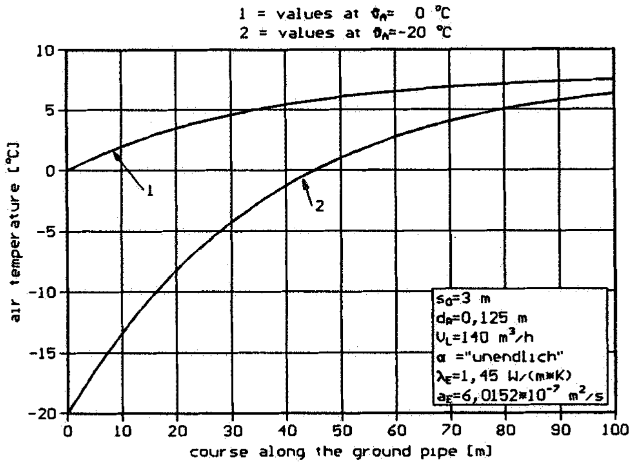

Fig. 13 Course of the air temperature in the pipe

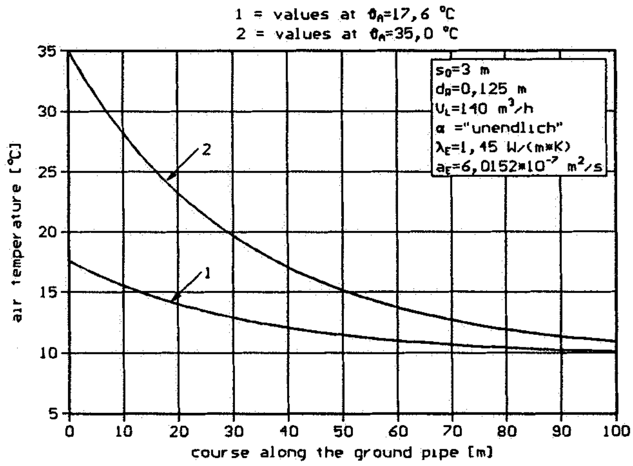

Fig. 14 Course of the air temperature in the pipe

Figs. 13 and 14 show the temperature course along the ground pipe in winter (month: January) and in summer (month: July). In each case, the temperature curve corresponding to the monthly mean value of the outdoor temperature (curve 1), together with the temperature curve resulting from a sudden extreme outdoor temperature (curve 2), are displayed. The extreme values are temperatures which can occur in Germany. Fig. 13 in conjunction with the above mentioned requirement gives the length of the ground heat exchanger under consideration here, laid at a depth of 3 m, to be 45 m.

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