5th International Conference on Air Distribution in Rooms

ROOMVENT '96

Vol. 1 July 17

CONFERENCE ORGANIZATION

Chairperson

S. Murakami (Japan)

Vice-chairperson

M. Kamata (Japan)
H. Yoshino (Japan)

Scientific Advisory Committee

F. Allard (France)
E. A. Arens (USA)
H. B. Awbi (UK)
A. J. Baker (USA)
L. L. Christianson (USA)
H. E. Feustel (USA)
G. V. Fracastoro (Italy)
D. T. Grimsrud (USA)
N. Ito (Japan)
K. Kimura (Japan)
T. Kusuda (USA)
K. H. Lee (Korea)
T. G. Malmström (Sweden)
A. Moser (Switzerland)
P. V. Nielsen (Denmark)
F. J. Offermann III (USA)
J. Ribéron (France)
M. Sandberg (Sweden)
J. Y. Sohn (Korea)
K. Y. Teichman (USA)
J. R. Waters (UK)
Y. W. Wu (China)
R. Y. Zhao (China)
N. Aratani (Japan)
G. Aubertin (France)
R. Aynsley (New Zealand)
D. Blay (France)
P. O. Fanger (Denmark)
K. Fitzner (Germany)
H. D. Goodfellow (Canada)
F. Haghighat (Canada)
P. Jackman (UK)
P. Kofoed (Switzerland)
J. Lebrun (Belgium)
M. W. Liddament (UK)
S. Mierzwinski (Poland)
M. Narasaki (Japan)
R. Niemelä (Finland)
U. Renz (Germany)
C. A. Roulet (Switzerland)
O. Seppänen (Finland)
E. Skåret (Norway)
P. O. Tjelflaat (Norway)
P. Wouters (Belgium)
S. Yoshizawa (Japan)

Secretariat

Secretary-General S. Kato (Japan)
Assistant Secretary-General S. Akabayashi (Japan)

Program Committeee

S. Akabayashi
S. Kato
S. Murakami
Y. Utsumi
M. Kamata
T. Kurabuchi
Y. Nagasawa
H. Yoshino

LOCALLY VENTILATED INDUSTRIAL BUILDING WITH HEAT RECOVERY: ENVIRONMENTAL TEMPERATURE INFLUENCE TO THERMAL COMFORT AND ENERGY CONSUMPTION

M. Bojić, professor
Mašinski fakultet
Sestre Janjić 6
34000 Kragujevac
Yugoslavia

N.Lukić, Teaching assistant
Mašinski fakultet
Sestre Janjić 6
34000 Kragujevac
Yugoslavia

M. Babić, Professor
Mašinski fakultet
Sestre Janjić 6
34000 Kragujevac
Yugoslavia

D. Milovanović, Assistant professor
Mašinski fakultet
Sestre Janjić 6
34000 Kragujevac
Yugoslavia

ABSTRACT
A study has been carried out of heat recovery from air that ventilates a hot tool in a tool shop. The recovered heat is used to preheat air for the space heating of this tool shop. Software has been used to analyze the heat-recovery efficiency and thermal comfort for a variation of environmental temperature. An increase of environmental temperature of 1K yields a heat saving of 2% and an increase of temperature in the tool shop of 2K. Additional adjustment of air flow for thermal comfort in the tool shop decreases heat expenditure for 1%. Contrary holds for a decrease of outside temperature.

KEYWORDS
Building, Thermal comfort, Energy consumption

1. INTRODUCTION
In some tool shops we use recovery- heat exchangers in winter to recover refuse heat of air used for local ventilation of hot tools of this tool shop. This refuse heat is used for preheating of air for space heating of tool shops. In previous paper (Bojić 1993) for this energy system we found that heat-saving efficiency is 2 to 12 % depending on used scenario for energy-flow control. We revealed the existence of an optimal scenario for minimum of energy consumption and the best thermal comfort in a tool shop.

Heat-recovery system usually operates in the conditions that are different than these defined by design. When the parameters of a tool-shop envelope and hot tool have no-design values it is shown (Bojić 1994; Bojić and Trnobransky 1995) that heat-saving efficiency and thermal comfort can be lower than defined by a design. Also, we have shown that then a heat-saving efficiency can be higher when we additionally improve a thermal comfort. As our energy system very rare operates with an fresh air having a design environmental temperature we here show the results for energy-saving efficiency and thermal comfort in the tool shop when an environmental temperature is variable.

For this study we have used simulation software AZMA (Bojić 1993). This software is based on a steady-state mathematical model of a tool shop by using the heat-exchanger network.

Although thermal comfort depends (Fanger 1970) on different factors, we have taken the thermal comfort in the tool-shop space to be function only of the air temperature. We treat the special case where there is no heating of the plant space by hot tools. Also we have not taken into account the energy that is used for air flow in the system that is not the case in literature (Turner 1982; Mahon et al 1983).

2. HEAT-RECOVERY SYSTEM
Figure 1 shows the tool shop with the hot tool ventilated by the air taken from the tool-shop

space. Two fresh air streams are used for space heating of the tool shop. These air streams are heated in the heat exchangers by using steam. The temperature of the first air stream at the enterance of the first heat exchanger is equal to the temperature of the environment air. We designate this heat exchanger as the cold heat exchanger. Because the second air stream is preheated in the recovery-heat exchanger by using the hot refuse-ventilation air the temperature of the second air stream at the enterance of the second heat exchanger is higher than the temperature of the environment air. The second heat exchanger is designated as the hot heat exchanger.

When the pressure of the air in the tool shop is lower than atmospheric then the environment air infiltrate the tool shop. When this pressure is higher than atmospheric then the air from the tool shop leaks through the tool-shop envelope. When the pressure in the tool shop is equal to the pressure of the environment air then there is no infiltration or leak through the envelope of the tool shop. From the tools and their stands we take the air by using a fan and locally ventilate these tools. The hot tools are heated by using the heating oil with the temperature that is lot higher than the temperature of the ventilation air. In this way the heating oil additionally heats this air. In HRE this ventilation air preheats the fresh air used in the hot heat exchanger. The heat is also exchanged between the tool shop and the environment through the tool shop envelope.

3. HEAT-EXCHANGER NETWORK

Figure 2 shows the heat-exchanger network used to model the heat-recovery system of Figure 1.

For a particular heat exchanger, we have assumed that the product of its surface and coefficient of heat transfer Z=FU is a constant and a characteristic value of this heat exchanger. For space heating, we use two heat exchangers: hot heat exchanger and cold heat exchanger. Every of these heat exchangers is modeled by heat exchanger with the heating fluid that has constant temperature. The tools and their stands are also modeled by using this kind of heat exchanger. The heat exchange process through the tool-shop envelope is modeled by using a heat exchanger where its lower temperature air is the environment air and has the constant temperature.

The mass and energy balance equations are

$$m_b=m_t+m_h+m_u, \quad (1)$$
$$m_d=m_b-m_i, \quad (2)$$
$$t_{bu}=(m_h t_{hi}+m_t t_{ti}+m_u t_a)/m_b, \quad (3)$$
$$t_{ti}=t_{tw}-(t_{tw}-t_{tu})\exp[-Z_t/(m_t c)], \quad (4)$$
$$t_{hi}=t_{hw}-(t_{hw}-t_a)\exp[-Z_h/(m_h c)], \quad (5)$$
$$t_{bi}=t_a-(t_{bu}-t_a)\exp[-Z_b/(m_b c)], \quad (6)$$
$$t_{di}=t_{dw}-(t_{dw}-t_{bi})\exp[-Z_d/(m_d c)], \quad (7)$$
$$t_{ri}, t_{tu}=f(t_{di}, t_a, m_d, c, m_t, c, Z_r). \quad (8)$$

We take t_{tw}, t_{hw} and t_{dw} to have constant values. All relationships of the general equation (8) are given in Appendix 1.

The heat fluxes are

$$q_t=m_t c(t_{ti}-t_{tu}), \quad (9)$$
$$q_h=m_h c(t_{hi}-t_a), \quad (10)$$
$$q_d=m_d c(t_{di}-t_{bi}). \quad (11)$$

The energies spent in the energy system without and with recovery-heat exchanger and the efficiency of heat recovery are

$$q_n=(q_t)_n+(q_h)_n+(q_d)_n, \quad (12)$$
$$q=q_t+q_h+q_d, \quad (13)$$
$$E=(q_n-q)/q_n. \quad (14)$$

The thermal comfort coefficient is

$$C=(t_{bi}-t_a)/(t_{tk}-t_a)-1. \quad (15)$$

We assume that an optimal thermal comfort in a tool shop is for $t_{bi}=t_{tk}$. Then, C=0. For non-recovery case also C=0. For $t_{bo}<t_{cf}$, $C_t<0$, for $t_{bo}>t_{cf}$, $C_t>0$, and there is no thermal comfort in a tool shop.

On retrofitting a particular non-recovery installation, the Z coefficients are obtained by using measurements on this installation. Details of this procedure are given in Appendix 2.

4. CONTROL SCENARIOS

If the pressure of the tool shop is atmospheric, the air does not infiltrate or leak through the envelope of the tool shop; $m_u=m_i=0$ and $m_t+m_h=m_b=m_d$. This is also the case without recovery-heat exchanger with $m_h=(m_h)_n$ and $m_c=(m_c)_n$ (the subscript n designates a system without recovery-heat exchanger). To reach the optimal thermal comfort temperature in the tool shop, we can adjust m_c and m_h together so $m_c+m_h=m_d$ holds. Then, for $m_h<(m_h)_n$ this is the VAT/L scenario, for $m_h>(m_h)_n$ this is the VAT/H scenario.

When the air pressure in the tool shop is lesser than atmospheric the fresh air infiltrates the tool shop. This is the case of the heat-recovery system when we keep m_c=const and adjust m_h to reach the optimum thermal comfort in the tool shop. For $m_h<(m_h)_n$ and $(m_h+m_c)<m_d$ the pressure in the tool shop is below atmospheric. This is the VAL/L scenario. In this case the total mass flow entering the tool shop is $m_b=m_h+m_c+m_i=m_d$ with $m_o=0$.

5. DESIGN VS OPERATIONAL PARAMETERS

We have designed our heat-recovery system to operate optimally for a value $(t_a)_m$ of the

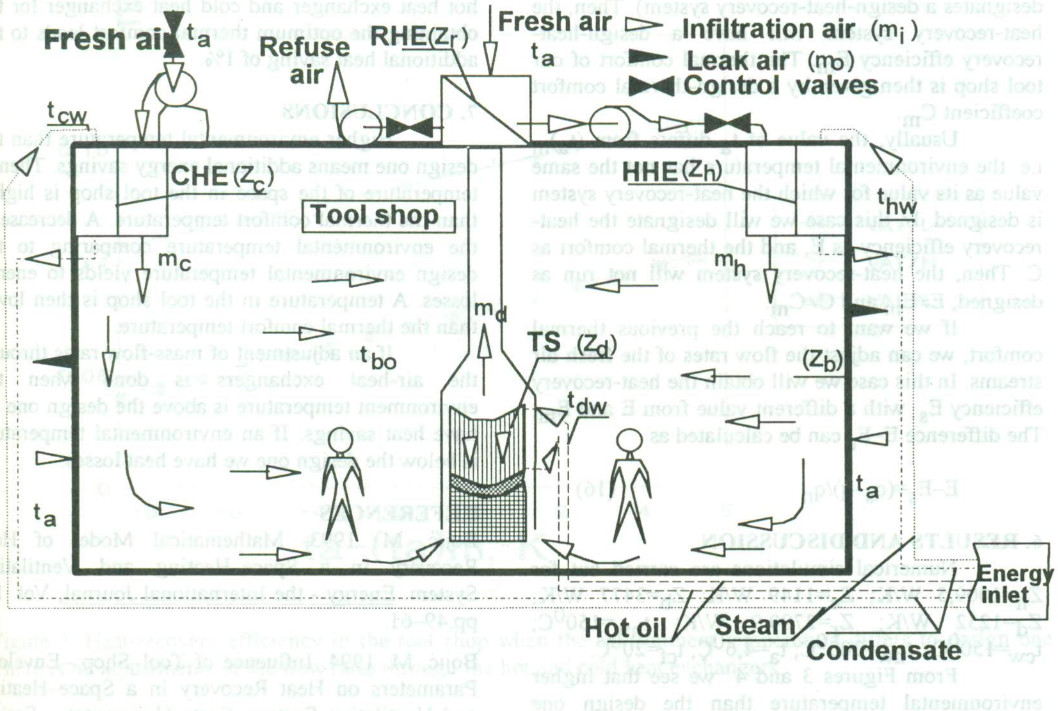

Figure 1. Heat-flow schema of the tool shop

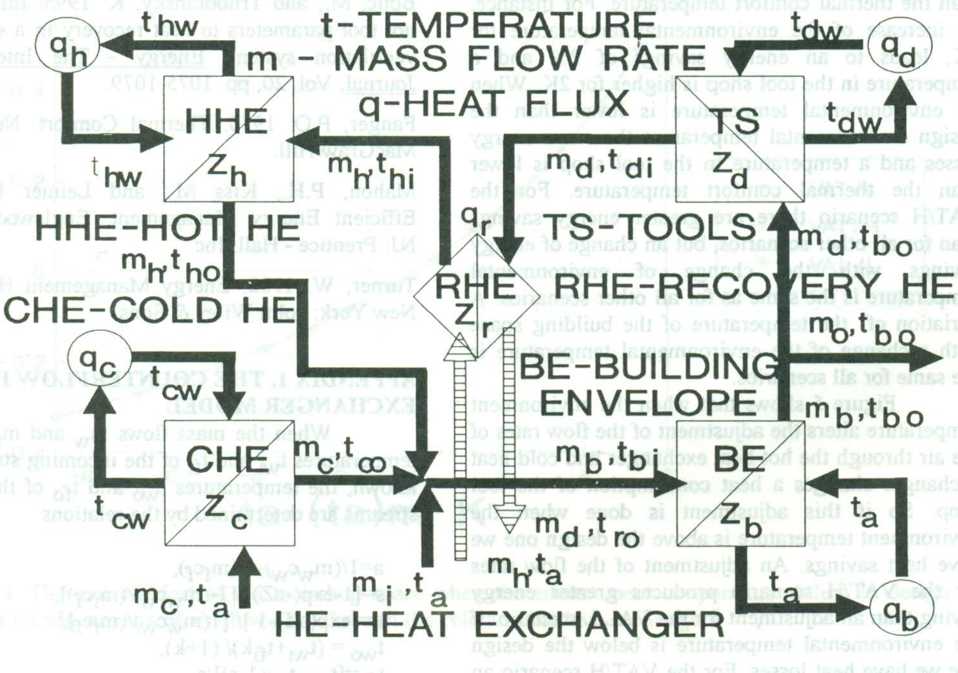

Figure 2. Heat-exchanger network.

environmental temperature has (the subscript m designates a design-heat-recovery system). Then, the heat-recovery system will have a design-heat-recovery efficiency E_m. The thermal comfort of our tool shop is then given by a design-thermal comfort coefficient C_m.

Usually, the value of t_a differs from $(t_a)_m$ i.e. the environmental temperature has not the same value as its value for which the heat-recovery system is designed. In this case we will designate the heat-recovery efficiency as E, and the thermal comfort as C. Then, the heat-recovery system will not run as designed; $E \neq E_m$ and $C \neq C_m$.

If we want to reach the previous thermal comfort, we can adjust the flow rates of the fresh air streams. In this case we will obtain the heat-recovery efficiency E_s with a different value from E and E_m. The difference $E - E_s$ can be calculated as

$$E - E_s = (q_s - q)/q_n. \quad (16)$$

6. RESULTS AND DISCUSSION

Numerical simulations are carried out for Z_h=1009,5 W/K; Z_c=1149 W/K; Z_b=3477 W/K; Z_d=1232 W/K; Z_r=2790,9 W/K; $t_{hw}=150^0C$; $t_{cw}=150^0C$; $t_{dw}=300^0C$; $t_a=4{,}6^0C$; $t_{cf}=20^0C$.

From Figures 3 and 4 we see that higher environmental temperature than the design one means additional energy savings. Then, the temperature of the space in the tool shop is higher than the thermal comfort temperature. For instance, an increase of the environmental temperature for 1K, leads to an energy savings of 2% and a temperature in the tool shop is higher for 2K. When an environmental temperature is lower than the design environmental temperature there are energy losses and a temperature in the tool shop is lower than the thermal comfort temperature. For the VAT/H scenario there are greater energy savings than for all other scenarios, but an change of energy savings with the change of environmental temperature is the same as for all other scenarios. A variation of the temperature of the building space with a change of the environmental temperature is the same for all scenarios.

Figure 5 shows that when the environment temperature alters the adjustment of the flow rates of the air through the hot heat exchanger and cold heat exchanger changes a heat consumption of the tool shop. So if this adjustment is done when the environment temperature is above the design one we have heat savings. An adjustment of the flow rates for the VAT/H scenario produces greater energy saving than an adjustment for the VAL/L scenario. If the environmental temperature is below the design one we have heat losses. For the VAT/H scenario an adjustment means higher energy losses than this the case with other scenarios. For the previous example the adjustment of the flow rate of the air through the hot heat exchanger and cold heat exchanger for the obtaining the optimum thermal comfort leads to the additional heat saving of 1%.

7. CONCLUSIONS

Higher environmental temperature than the design one means additional energy savings. Then, a temperature of the space in the tool shop is higher than the thermal comfort temperature. A decrease of the environmental temperature comparing to the design environmental temperature yields to energy losses. A temperature in the tool shop is then lower than the thermal comfort temperature.

If an adjustment of mass-flow rates through the air-heat exchangers is done when the environment temperature is above the design one we have heat savings. If an environmental temperature is below the design one we have heat losses.

REFERENCES

Bojić, M. 1993. Mathematical Model of Heat Recovery in a Space–Heating and Ventilation System. Energy - the International Journal, Vol. 18, pp.49–61.

Bojić, M. 1994. Influence of Tool–Shop –Envelope Parameters on Heat Recovery in a Space–Heating and Ventilation System. Facta Universitatis, Series: Mechanical Engineering Vol. 1, No 1, pp.65–71.

Bojić, M.; and Trnobransky, K. 1995. Influence of hot tool parameters to heat recovery in a space and ventilation system. Energy - The International Journal, Vol. 20, pp. 1075-1079.

Fanger, P.O. 1970. Thermal Comfort. New York: MacGraw-Hill.

Mahon, P.H.; Kiss M.; and Leimer H. 1983. Efficient Energy Management. Englewood Cliffs, NJ: Prentice - Hall, Inc.

Turner, W. 1982. Energy Management Handbook. New York: John Wiley & Sons.

APPENDIX 1. THE COUNTERFLOW HEAT-EXCHANGER MODEL

When the mass flows m_w and m_f and the temperatures t_{wi} and t_{fi} of the incoming streams are known, the temperatures t_{wo} and t_{fo} of the exiting streams are determined by the relations

$$a = 1/(m_w c_w) - 1/(m_f c_f), \quad (17)$$

$$s = [1 - \exp(-aZ)]/[1 - (m_w c_w)/(m_f c_f)], \quad (18)$$

$$k = [\exp(aZ) - 1]/[1 (m_w c_w)/(m_f c_f], \quad (19)$$

$$t_{wo} = (t_{wi} + t_{fi} k)/(1 + k), \quad (20)$$

$$t_{fo} = [t_{wo} - t_{wi}(1 - s)]/s. \quad (21)$$

The general form of the this set of equations is

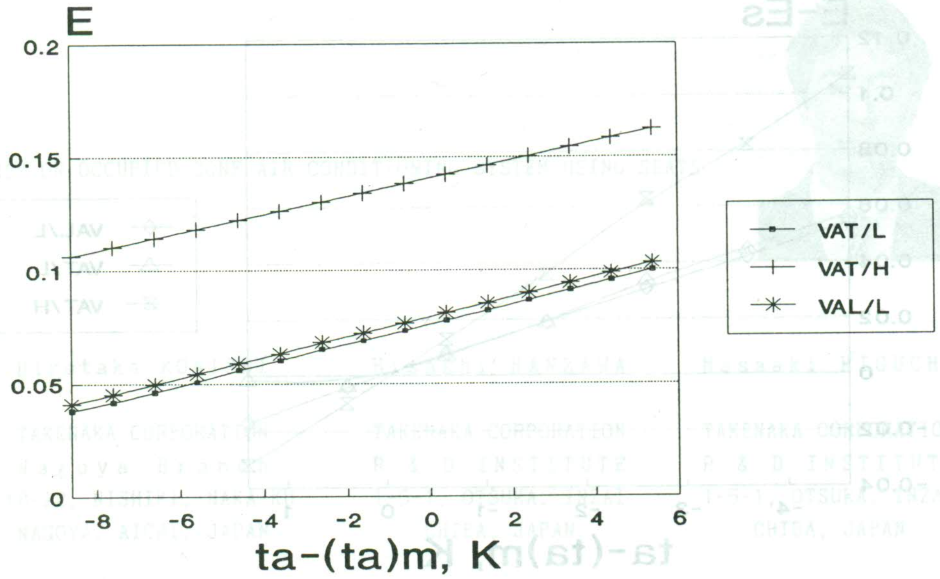

Figure 3. Heat-recovery efficiency in the tool shop when the environment temperature differs to design one There is no adjustments of the flow rates through the hot and cold heat exchangers.

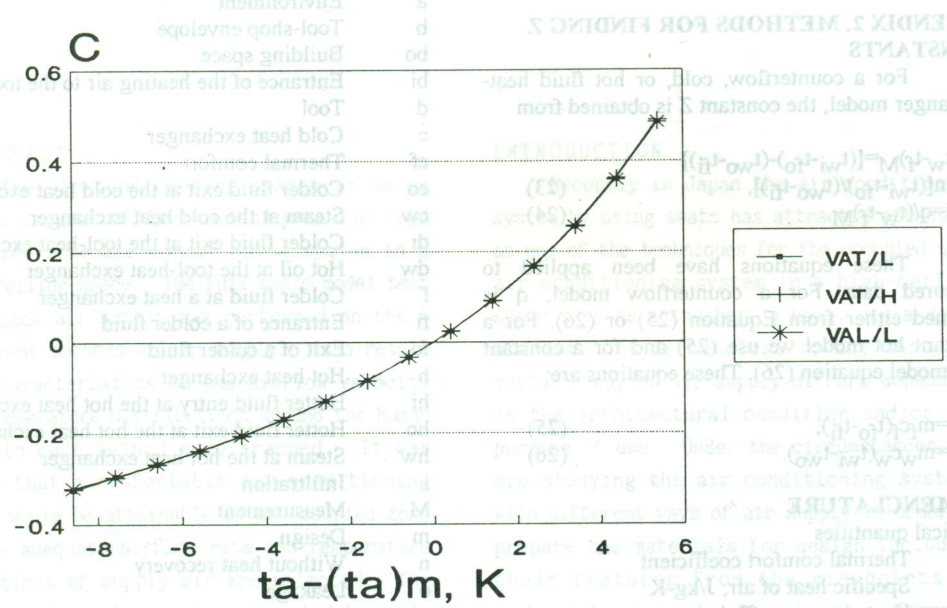

Figure 4. Thermal comfort of the tool-shop space when the environment temperature differs to design one There is no adjustments of air-flow rates through the cold and hot heat exchangers.

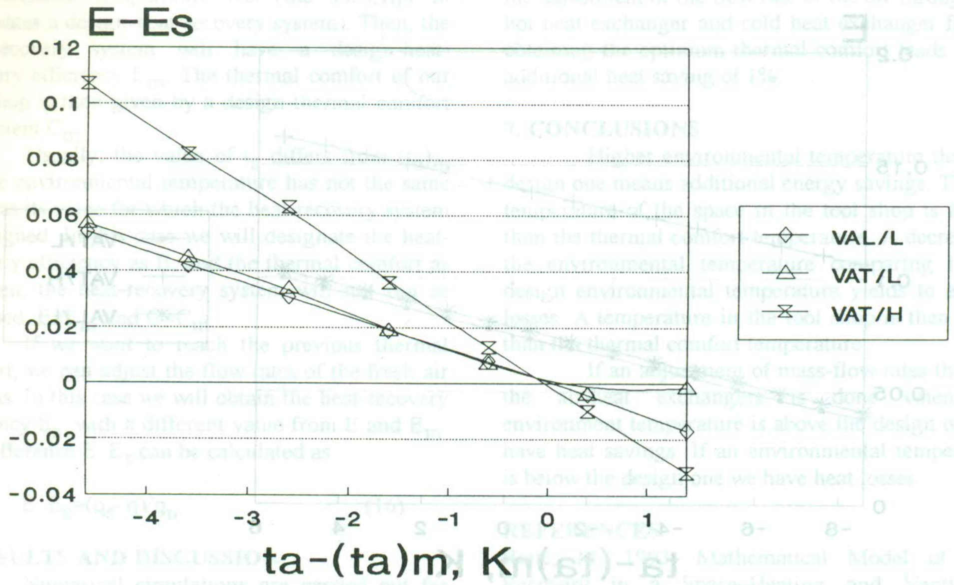

Figure 6 The difference of the heat-recovery efficiency with and without an adjustment of the air-flow rat through the cold heat exchanger and hot heat exchanger

$$t_{wo}, t_{fo} = f(t_{wi}, t_{fi}, m_w, c_w, m_f, c_f, Z). \quad (22)$$

APPENDIX 2. METHODS FOR FINDING Z CONSTANTS

For a counterflow, cold, or hot fluid heat-exchanger model, the constant Z is obtained from

$$(t_w - t_f)_M = [(t_{wi} - t_{fo}) - (t_{wo} - t_{fi})] / \ln[(t_{wi} - t_{fo})/(t_{wo} - t_{fi})], \quad (23)$$

$$Z = q/(t_w - t_f)_M. \quad (24)$$

These equations have been applied to measured data. For a counterflow model, q is obtained either from Equation (25) or (26). For a constant hot model we use (25) and for a constant cold model equation (26). These equations are:

$$q = m_f c_f (t_{fo} - t_{fi}), \quad (25)$$

$$q = m_w c_w (t_{wi} - t_{wo}). \quad (26)$$

NOMENCLATURE

Physical quantities

C	Thermal comfort coefficient
c	Specific heat of air, J/kg-K
E	Heat-recovery efficiency
F	Heat-transfer surface, m^2
m	Mass-flow rate, kg/s
q	Heat flux, W
t	Temperature, ^0C
U	Heat-transfer coefficient, $W/(m^2K)$
Z	Heat-transsmitance coefficient, W/K

Indices

a	Environment
b	Tool-shop envelope
bo	Building space
bi	Entrance of the heating air to the tool shop
d	Tool
c	Cold heat exchanger
cf	Thermal comfort
co	Colder fluid exit at the cold heat exchanger
cw	Steam at the cold heat exchanger
di	Colder fluid exit at the tool-heat exchanger
dw	Hot oil at the tool-heat exchanger
f	Colder fluid at a heat exchanger
fi	Entrance of a colder fluid
fo	Exit of a colder fluid
h	Hot heat exchanger
hi	Hotter fluid entry at the hot heat exchanger
ho	Hotter fluid exit at the hot heat exchanger
hw	Steam at the hot heat exchanger
i	Infiltration
M	Measurement
m	Design
n	Without heat recovery
o	Leakage
r	Recovery-heat exchanger
rw	Hot fluid exit: the recovery heat exchanger
s	Adjustment
w	Hotter fluid at a heat exchanger
wi	Entrance of a hotter fluid
wo	Exit of a hotter fluid