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ABSTRACT

The indoor air quality in buildings is ensured by mechanical ventilation with a sufficient outside air flow rate according to national or European regulations. The sufficient outside air flow rate but in traditional view increases the heat demand of buildings and the higher the air flow rate the higher is the energy demand; hence man is likely to reduce the air flow rate in order to save energy. The consideration of this point is that mechanical ventilation systems with constant volume rate are replaced by ones with variable volume rates. This investigation shows significant energy conservation potential by optimization of air flow rate. A typical office room for two occupants in an EnEV 2009 and WSchV 82 building is used as investigated model in the study respectively. The software TRNSYS is used for the assessment of annual energy demand for heating and cooling of the room.

1. INTRODUCTION

A technical combination of the operation of heating, cooling and mechanical ventilation provides at the same time thermal comfort and indoor air quality in office buildings, where occupants usually stay day long for work. The indoor air quality in buildings is ensured by mechanical ventilation with a sufficient outside air flow rate according to national or European regulations DIN EN 15251 (2007) and DIN EN 13779 (2007). The sufficient outside air flow rate but in traditional view increases the heat demand of buildings and the higher the air flow rate the higher is the energy demand. Referring to the demand of oxygen the required outside air flow rate could be reduced to less than a one-tenth of rates that are common today. Hence man is likely to reduce the air flow rate in order to save energy. Therefore, the consideration of this point is that mechanical ventilation systems with constant volume rate are replaced by ones with variable volume rates. The goal of this optimization is to minimize the annual useful energy demand for heating, cooling and the energy demand of the transport of the air in the mechanical ventilation system. An objective function performs the optimizing the air flow rate of the mechanical ventilation. The declining indoor air quality due to the reduction of the air flow rate must be compensated by a pollutant sink (air cleaner).

A room of an office building is used as model for the case study respectively. A self-developed program combined with the software TRNSYS (TRaNsient SYstems Simulation) (2010) is used as a tool for this investigation. Four scenarios are performed for the estimations of the annual useful energy demand and the primary useful energy demand for the room in an EnEV 2009 (2009) and a WSchV 82 (1982) building respectively.

The results show that there is a certain energy conservation potential by optimizing the outside air flow rate. The use of heat recovery ventilation has a similar energy conservation potential under the same conditions. It is noticeable that the room in the EnEV 2009 building demands more energy for cooling than for heating; and the energy demand is almost the same for the room without ventilation and with ventilation at 60 m³/h air flow rate. The ventilation shows its disadvantage in a good thermally insulated building.

2. METHODS

An objective function is programed for optimizing the air flow rate of the mechanical ventilation. The algorithm for the energy calculation is performed within the time step of TRNSYS iteratively by air flow rate calculated from minimum to maximum. The following sub-sections are presented for the calculation of the primary energy demand and friction losses respectively.

2.1 Energy Demand

The calculation of total energy demand is designed as primary energy demand. It consists of energy demand of heating or cooling and of transport of air by mechanical ventilation which is named *auxiliary energy of mechanical ventilation*, see equation (1).

$$\dot{Q}_{Tot} = \dot{Q}_{H/C} + \dot{Q}_{Vent,Aux} \tag{1}$$

Energy demand for heating or cooling is calculated in the following equation (2). It consists of internal thermal loads, the heat losses or gains through the surface of the rooms, solar gains through windows, heat losses through mechanical ventilation and infiltration.

$$\dot{Q}_{H/C} = \dot{Q}_{intern.\ load} + \dot{Q}_{Tr} + \dot{Q}_{Solar} + \dot{Q}_{Vent} + \dot{Q}_{Inf} \tag{2}$$

The internal thermal loads, the transmission losses/gains of surfaces, the losses by infiltration and the solar gains can be merged to the difference between heating/cooling demand and heat losses through ventilation; it is defined here as $\dot{Q}_{rest,load}$. And then the equation (2) can be reformed to equation (3).

$$\dot{Q}_{H/C} - \dot{Q}_{Vent} = \dot{Q}_{intern.\ load} + \dot{Q}_{Tr} + \dot{Q}_{Solar} + \dot{Q}_{Inf} = \dot{Q}_{rest,load} \tag{3}$$

Equation (3) is shorted to equation (4)

$$\dot{Q}_{H/C} = \dot{Q}_{rest\ load} + \dot{Q}_{Vent} \tag{4}$$

Equation (1) is now reformed to equation (5) with a consideration of factors for heating or cooling and auxiliary energy of mechanical ventilation.

$$\dot{Q}_{Tot} = f_{H/C} \cdot \left(\dot{Q}_{rest,load} + \dot{Q}_{Vent}\right) + f_{Aux} \cdot \dot{Q}_{Vent,Aux} \tag{5}$$

The heat losses through the mechanical ventilation and the auxiliary energy are functions of the air flow rate, see equation (6) and (7).

$$\dot{Q}_{Vent} = f(\dot{m}_{Vent}) = \dot{m}_{Vent} \cdot C_p \cdot (\vartheta_O - \vartheta_R) \tag{6}$$

$$\dot{Q}_{Vent,Aux} = f(\dot{m}_{Vent}) = \frac{\dot{m}_{Vent} \cdot \Delta P_{Tot}}{\eta_{Sys}} \tag{7}$$

The total pressure losses of the mechanical ventilation is defined in equation (8)

$$\Delta P_{Tot} = (\xi + l \cdot \frac{\lambda}{d}) \cdot \frac{1}{2} \cdot \rho \cdot v^2 \tag{8}$$

The velocity of air flow in the duct of ventilation system is defined in equation (9)

$$v = \frac{\dot{m}_{Vent}}{A} \tag{9}$$

From equation (8) and (9) the auxiliary energy of ventilation can be written in equation (10). The friction losses are discussed in the following section.

$$\dot{Q}_{Vent,Aux} = (\xi + l \cdot \frac{\lambda}{d}) \cdot \frac{1}{2 \cdot \rho^2 \cdot A^2 \cdot \eta_{Sys}} \cdot \dot{m}_{Vent}^3 \tag{10}$$

2.2 Friction losses of mechanical ventilation

According to the Colebrook's equation the friction factor for completely turbulent flow in ducts needs to be solved iteratively, the Altshul-Tsal equation (11) in ASHRAE (2009) is used here for solving the friction factor and its deviation is within 1.6%.

$$f' = 0.11(\frac{\varepsilon}{d_h} + \frac{68}{Re})^{0.25} \tag{11}$$

If $f' \geq 0.018: f = f'$

If $f' < 0.018: f = 0.85f' + 0.0028$

The Reynolds number Re is defined in equation (12)

$$Re = \frac{v \cdot d_h}{\nu} \tag{12}$$

3. MODEL AND BOUNDARY CONDITIONS

3.1 Room model

An office room in an EnEV 2009 and a WSchV 82 building respectively is chosen for the investigation. The building is located in the climate zone TRY 12 (2004) of Germany. The room orientates to the south and is 7.2 m long, 4.2 m wide and 2.5 m high. The window is 7.2 m long and 1.5 m high; the breast is 7.2 m long and 1.0 m high. The property of window and construction of walls are descripted in table 1. Only window and breast are external surfaces, the other surfaces of the room are all internal.

Table 1: Property of room surfaces

	Type	U - Value	G - Value
Window (EnEV 2009)	2-WVS Argon	1.40	0.622
Window (WSchV 82)	ISOLIER	2.80	0.755
Breast (EnEV 2009)	-	0.24	-
Breast (WSchV 82)	-	0.64	-
Internal walls	-	1.00	-
Ceiling	-	0.42	-
Floor	-	0.33	-

3.2 Ventilation model

The ventilation model is created with Type 56-TRNFLOW (2009) for the mechanical ventilation system. Figure 1 illustrates the supply exhaust system which connects the environment with ducts.

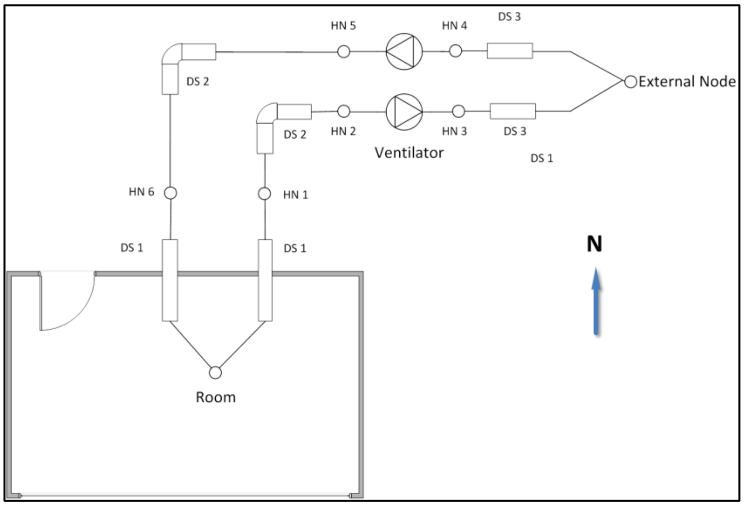

Figure 1: Schematic illustration of the mechanical ventilation in TRNFLOW

3.3 Boundary conditions

The internal loads in the room consist of thermal and material loads. The thermal load consists of occupants, electric equipment and light. Two occupants sit in the room. Every one emits 70 W of sensible heat and 80 g/h of humidity. The electric equipment has a thermal output of 10 W/m² and the lights of 15 W/m² according to SIA – Merkblatt 2024 (2006). The mechanical ventilation is used for the removal of CO_2 which is emitted by the occupants. The thermal loads are covered by ideal heating and cooling systems. The relative air humidity is kept between 30% and 55% with humidification and dehumidification.

In order to estimate the energy demand under the varied scenarios, it is necessary to define some full year profiles. The thermal load profiles which include the loads by occupants, electric equipment (computer, monitor, printer and copy machine) and the lights are defined according to SIA – Merkblatt 2024 (2006) as well. They preform only from 7 to 18 o'clock on work days. The set values for heating is 21 °C on work days and 18°C beyond this time, also at weekend; and cooling 26°C on work days and 28°C on the rest of the time. The mechanical ventilation performs from 8 to 18 o'clock on work days. An external shade is set up for the window and performs with a shade factor 0.5 from 10 to 15 o'clock.

The external air temperature is considered directly as supply temperature of the mechanical ventilation for the studies besides one case with heat recovery ventilation (HRV). The HRV is set only for January, February, March and December, because the energy conservation is profitable only in these four months of the year. The heat recovery factor is 0.75. Because the EnEV 2009 building is highly tight, the infiltration of the room is ignored. It isn't also considered for the WSchV 82 building for comparison reasons.

3.4 Parameters in the developed program and cases of investigation

The parameters for optimizing the air flow rate in the program are defined in table 2. The primary energy factors for heating and auxiliary energy are 1.1 and 2.6 according to DIN V 18599 (2011) respectively. The primary energy factor for cooling is 0.87. The range of the optimized air flow rate is defined in this study from 1.2 m³/h (1.44 kg/h) to 60 m³/h (72 kg/h); 1.2 m³/h (1.44 kg/h) air flow rate is considered as the minimum need of oxygen for two occupants in the room according to Kunsch (2000) and 60 m³/h (72 kg/h) as the guarantee of CO_2-concentration maximum to 1000 ppm according to Recknagel, Sprenger, Schramek (2005/06).

Four scenarios are defined for the investigation in an EnEV 2009 and a WSchV 82 building respectively. The first scenario is a ventilation system with an air flow rate of 0 m³/h. The second scenario is the ventilation with the optimization of air flow rate. The third scenario is the ventilation with a constant value of 60 m³/h and HRV and the last scenario is the ventilation with a constant value of 60 m³/h without HRV.

Table 2: Values of parameters in the developed program

Description	Symbol	Value	Description	Symbol	Value
Heat capacity of air [kJ/(kgK)]	C_p	1006	Primary energy factor for heating [-]	$f_{p,H}$	1.1
Local resistance [-]	ξ	4.6	Primary energy factor for cooling [-]	$f_{p,C}$	0.87
Efficiency of ventilation system	η	0.5	Primary energy factor for auxiliary energy [-]	$f_{p,Aux}$	2.6
Diameter of duct [m]	d	0.07	Minimal air flow rate [kg/h]	$\dot{m}_{Vent,min}$	1.44
Length of duct [m]	l	20	Maximal air flow rate [kg/h]	$\dot{m}_{Vent,max}$	72
Roughness of duct [mm]	ε	0.01	Step of air flow rate [kg/h]	$\Delta\dot{m}_{Vent}$	1.0
Kinematic viscosity [m²/s]	ν	1.58e-05			

4. RESULTS

Only the relevant and representative results of this investigation are shown in this paper. Figure 2 presents four scenarios with a stacked diagram for the annual hourly room air temperature for the EnEV 2009 building. The external temperature and room temperature are displayed from the bottom of diagram to the top for the four scenarios respectively. For the third scenario with HRV it is shown the supply temperature after HRV. The room air temperatures of the WSchV 82 building have the similar trend of annual hourly air temperature; therefore they are not shown in this paper.

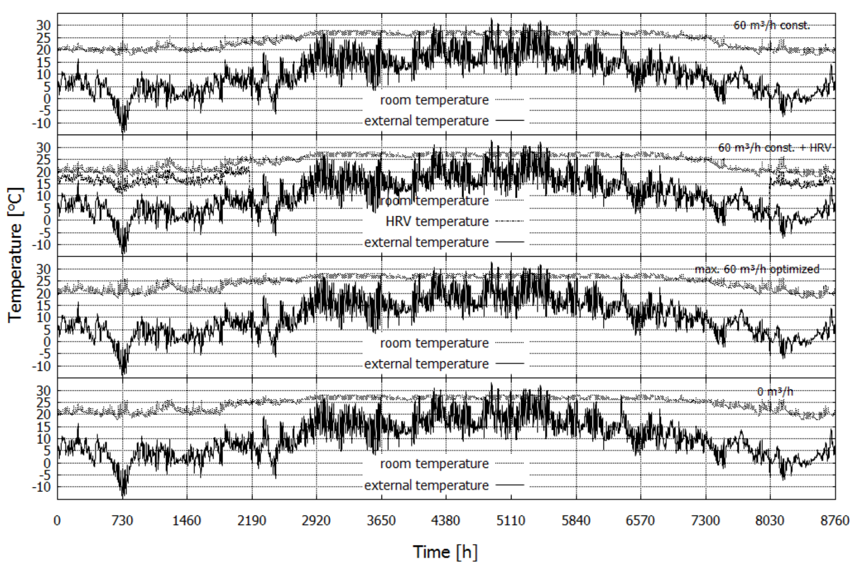

Figure 2: Annual hourly room air and supply air temperature for the EnEV 2009 building

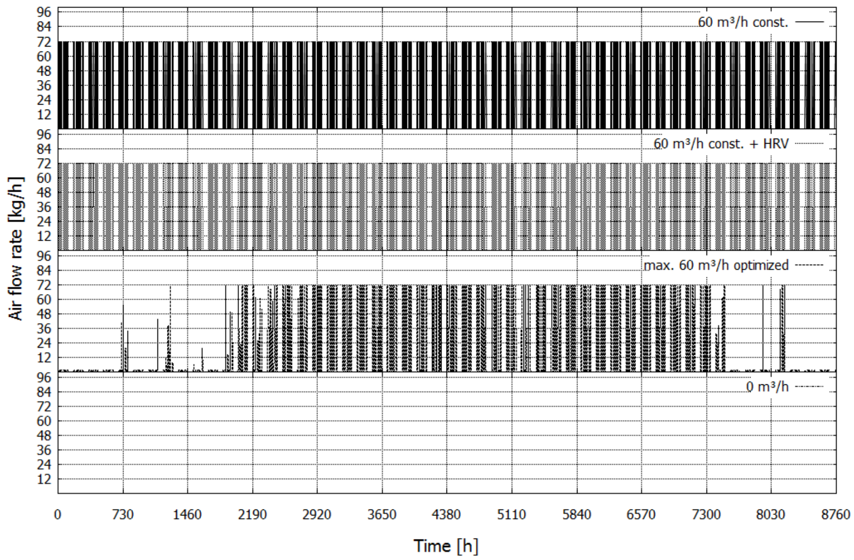

Figure 3: Annual hourly air flow rate of mechanical ventilation for the EnEV 2009 building

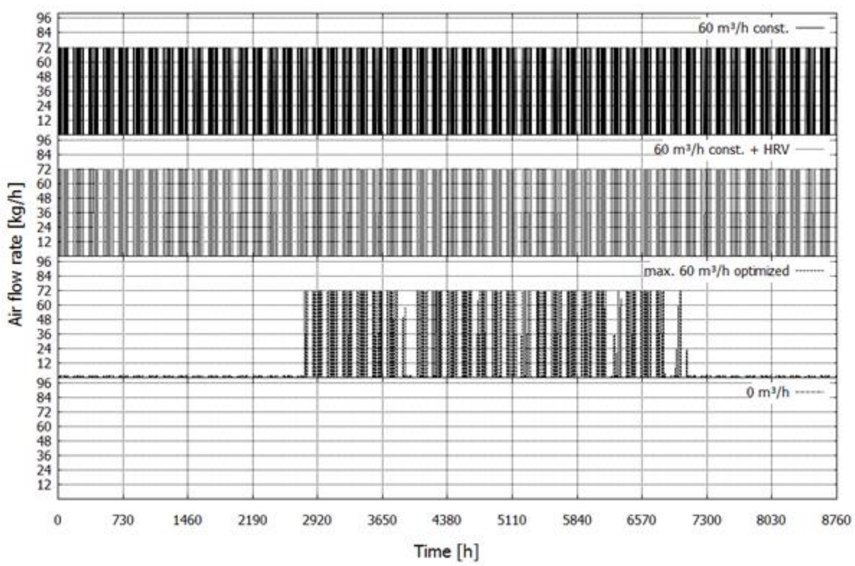

Figure 4: Annual hourly air flow rate of mechanical ventilation for the WSchV 82 building

Figure 3 and 4 show the annual hourly air flow rate for the EnEV 2009 and the WSchV 82 building respectively. The illustration is presented in a form of stacked diagram as well. The air flow rates are shown in the diagram with the unit kg/h. It should be interesting about the behavior of the air flow rates in the scenario with a maximum of 60 m³/h optimized. The control for the optimizing air flow rates is automatically switched off in winter and conversely switched on in summer. “Off” in winter is obviously profitable for the primary energy saving by the ventilation system, because the use of external air as supply air causes a higher energy demand in order to achieve the room set temperature. On the other side the external air temperature most of the time is lower than the room temperature in summer, spring and autumn; therefore a direct use of external air can partly compensate the energy demand by the cooling load in the room.

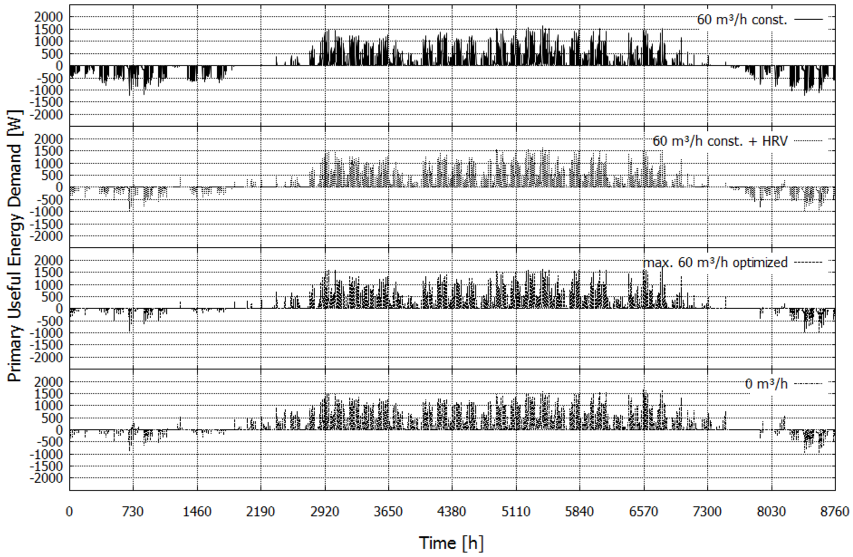

Figure 5: Annual hourly primary useful energy demand for the EnEV 2009 building

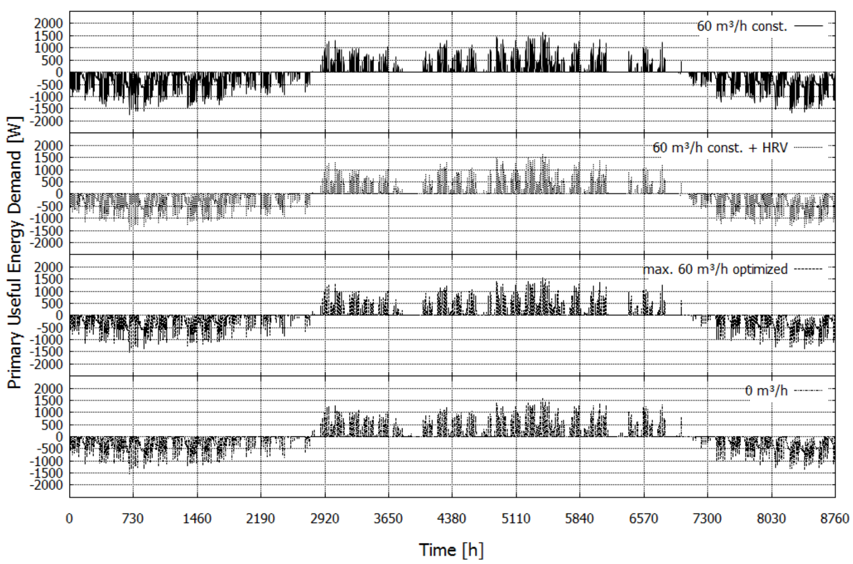

Figure 6: Annual hourly primary useful energy demand for the WSchV 82 building

Figure 5 and 6 show the annual hourly primary useful energy demand in four scenarios for both buildings. The energy demand has a unit in Watt in the diagram. The EnEV 2009 building has a higher useful energy demand for cooling in summer and in contrast the WSchV 82 building for heating in winter.

Figure 7 shows the annual useful energy demand and primary useful energy demand in beam form for the EnEV 2009 and the WSchV 82 building. The energy demand is illustrated for full year in kWh/(m²a). The upper beams are displaying the heating part of the energy demand and the lower beams the cooling part. The useful energy demand is shown on the left side of the diagram and the primary energy demand on the right side. The EnEV 2009 building has a lower energy demand for heating especially for “no ventilation performance” or “optimized performance". The constant air flow rate raises the energy losses in winter. The performance of the HRV can reduce the energy losses in winter. But "no ventilation" and the ventilation with a constant air flow rate of 60 m³/h have almost the same annual energy demand. The optimized ventilation has best results for the conservation of energy. The WSchV 82 building has a similar trend as the EnEV 2009 building but it has a higher energy demand in total; such a building is sure to have a higher energy demand for heating because of the worse heat transmission coefficient of the window and the wall. The primary useful energy demand is lower for the EnEV 2009 building because the cooling in such buildings plays a central role for the energy demand. Conversely the WSchV 82 building has a higher primary useful energy demand than useful energy demand.

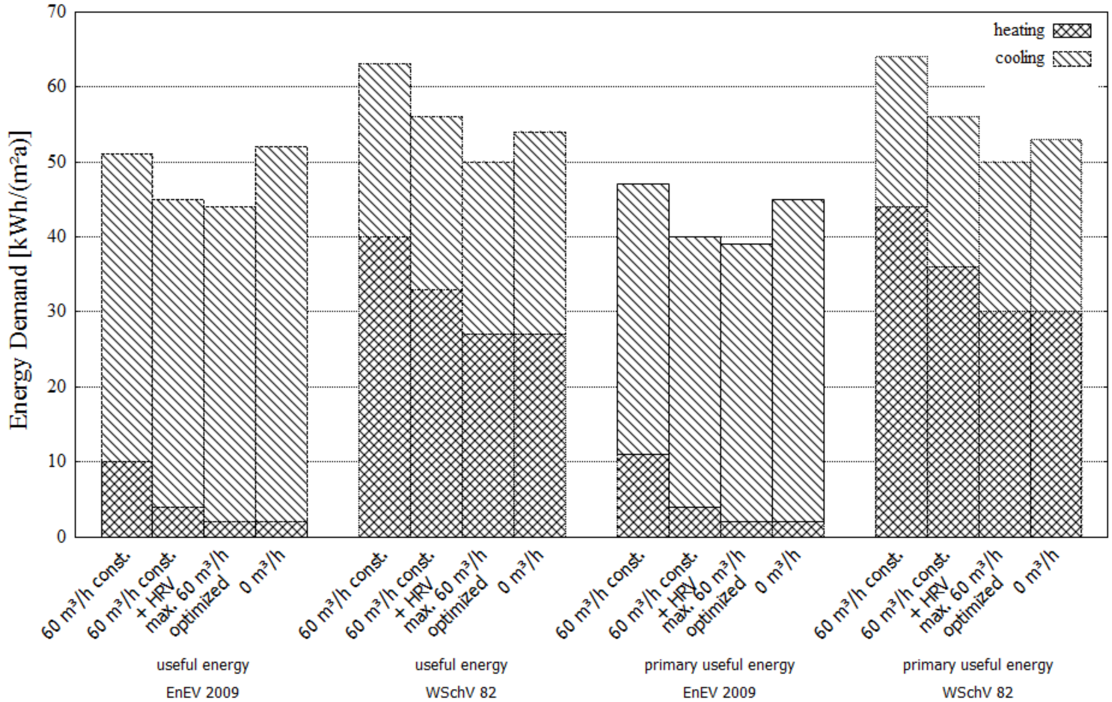

Figure 7: Comparison of annual useful energy demand and primary useful energy demand for EnEV 2009 and WSchV 82 building

Table 3: Energy conservation potential of useful energy and primary useful energy for EnEV 2009 and WSchV 82 building

	Useful energy EnEV 2009		**Useful energy WSchV 82**		**Primary useful energy EnEV 2009**		**Primary useful energy WSchV 82**	
60 m³/h const.	51	Ref.	63	Ref.	47	Ref.	64	Ref.
60 m³/h const. + HRV	46	-10%	56	-12%	41	-13%	57	-12%
max. 60 m³/h optimized	44	-13%	51	-20%	40	-16%	51	-21%
0 m³/h	52	2%	55	-14%	46	-2%	54	-16%

The energy conservation potential is shown in table 3 in percentage. In the view of useful energy demand only the EnEV 2009 building without ventilation needs a little bit more energy than the reference case. The optimized ventilation can significantly reduce the energy demand.

5. CONCLUSIONS

This presented study demonstrates the energy conservation potential only through the control of the air flow rate of the ventilation. It proves a point that in the view of energy demand especially of primary energy demand the ventilation with higher air flow rates does not always have disadvantages. The ventilation can compensate the cooling load of buildings. This control strategy bares more benefits for the “old” WSchV 82 building in this investigation than the “new” EnEV 2009 building. The application of the HRV in the ventilation can reduce the energy demand in case of operating only in winter; otherwise the energy demand would increase.

In the future the useful upper limit of the air flow rate for the optimization should be investigated with this developed tool.

NOMENCLATURE

A	Area	(m²)
C_p	Heat capacity	(kJ/(kgK))
d	Diameter	(m)
f	Factor / friction factor	(-)
f'	Temporary friction factor	(-)
l	Length of duct	(m)
$\dot{m}$	Air flow rate	(kg/h)
ΔP	Pressure losses	(Pa)
$\dot{Q}$	Energy demand	(kJ/h)
Re	Reynolds number	(-)
v	Velocity in duct	(m/s)
ε	Material absolute roughness factor	(mm)
η	Efficiency of ventilation	(-)
ϑ	Temperature	(°C)
ρ	Density of air	(kg/m³)
ν	Kinematic viscosity	(m²/s)
ξ	Local resistance	(-)

Subscript

Aux	Auxiliary
C	Cooling
h	Hydraulic
H	Heating
Inf	Infiltration
max	Maximum
min	Minimum
p	Primary
Sys	System
Tot	Total
Tr	Transmission
$Vent$	Ventilation

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