Energy-efficient hybrid dual-duct dual-fan systems

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Abstract. Reduction of energy demand for air treatment in dual-duct systems proves particularly challenging, due to simultaneous thermal treatment of two airflows with significantly varying temperature set-points. In pursuit of substantial energy savings for HVAC, we propose new hybrid dual-duct systems, which combine advantages of both extract air recirculation and heat recovery from exhaust air. To ensure energy-efficient performance of our hybrid systems, we propose appropriate technological design solutions for thermal treatment and automatic control. We also resolve problems caused by simultaneous use of heat recovery and air recirculation. The paper presents our technological solution for the hybrid dual-duct dual-fan system with a two-stage reduction of energy demand and our dedicated strategy for the system automatic control. Finally, we perform dynamic simulations of the proposed hybrid system under two-shift occupancy of ventilated rooms to quantify expected annual energy savings.

1 INTRODUCTION

In general dual-duct ventilation systems are designed to deliver temperature set-points in many rooms with different instantaneous thermal loads [7]. In these systems, two streams of supply air are centrally treated, namely a hot airflow and a cold airflow [10-11]. These airflows are subsequently distributed within the building and supplied to individual rooms. Prior to supplying to individual rooms, hot air is mixed with cold air in mixing boxes, in portions that ensure the required instantaneous temperature set-points. Portions of hot and cold air supplied to mixing boxes can vary significantly and be subject to ongoing adjustments during the use of individual rooms. These individual adjustments may be caused by changes in either external conditions (e.g. temperature, solar radiation) or internal room conditions (e.g. variable heat loads, variable air temperature set-points). Energy consumption of dual-duct systems can be relatively high due to simultaneous thermal treatment of two airflows with significantly varying temperature set-points [8]. A standard approach to reducing energy demand in HVAC involves modifying systems by adding either air recirculation or heat recovery [7].

2 REDUCTION OF ENERGY DEMAND FOR THERMAL TREATMENT

The simplest way to reduce the energy demand for air treatment is to use recirculated extract air for supply air. A common practice is to design recirculation with different portions of external air, such that the minimum external air supply requirement, under design conditions, is fulfilled. Different set-point conditions and variable portions of external airflow are used under transient conditions. The purpose of using variable external airflows in ventilation systems is to minimise the energy demand for thermal treatment of the ventilating airflow.
When using heat recovery from exhaust air, it is prudent to use the maximum heat recovery under both summer and winter design conditions. Under transient conditions, it is beneficial to adjust the efficiency of heat recovery to instantaneous requirements and periodically disable heat recovery. Changing the efficiency of heat recovery during transients should also minimise the energy demand for thermal air treatment.

Technological procedures, associated with both recirculation and heat recovery, are well-developed and thoroughly investigated for single-duct ventilation systems [10]. These procedures are, however, not straightforward for dual-duct systems.

The use of recirculation in dual-duct ventilation and air-conditioning systems is presented in many papers [1-14]. However, only few [6-8] include annual analysis of the variable portion of external air in the ventilating air and its impact on the primary energy demand for the treatment of supply air.

The reduction of the primary energy demand through heat recovery in dual-duct ventilation and air-conditioning systems and the efficiency of heat recovery in the annual cycle are only discussed in [7].

We are not aware of any solutions in the literature showing the simultaneous use of extract air recirculation and heat recovery from exhaust air to minimise the primary energy demand for air treatment in dual-duct systems.

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Fig. 1. - Fig. 3. show schematics of technological design solutions, where the above-mentioned possibilities to limit the energy demand for air treatment are applied to dual-duct systems with two supply fans.

Fig. 1. shows a schematic of a dual-duct system with extract air recirculation, in which recirculation is individually controlled for the cold and hot air subsystems, respectively. This technological design solution allows the use of different external air portions in each subsystem, thus ensuring the reduction of energy consumption for air treatment processes in a yearly cycle.

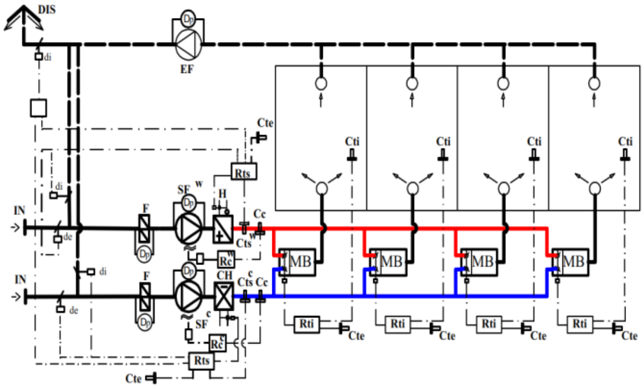

Fig. 1. Schematic of a dual-duct dual-fan ventilation system with individual extract air recirculation for cold and hot air subsystems.
Key: IN – air intake, d – damper, F – filter, Dp – pressure control, SF – supply air fan, c – cold air, w – hot air, H – heating coil, CH – cooling coil, EF – extract air fan, MB – mixing box, DIS – air discharge, Ct – temperature sensor, e – external air, i – room air, s – supply air, r – air mixture, R – regulator, Rc – pressure regulator, Rt – temperature regulator, Cc – pressure sensor.

Fig. 2. shows a schematic of a dual-duct system with heat recovery from exhaust air, in which the efficiency of heat recovery from exhaust air is individually controlled to heat the external airflows distributed into the cold and hot air subsystems, respectively. The diversity of the efficiency of heat recovery is obtained by using the bypass of the heat recovery exchanger through which periodically a portion of the external air is distributed. This technological design solution allows obtaining different temperatures of pre-treated external air in both supply airflows. As a result, the overall energy consumption in the annual cycle for the final air treatment processes is minimised, particularly in the case of cold air subsystem. This design solution, involving the diversified preheat of external air, allows for the maximum use of heat recovery from the exhaust air to heat the external air distributed into the hot air subsystem. Simultaneously, the external air parameters in the winter and transitional periods can be used to set the temperature of the treated cold air.

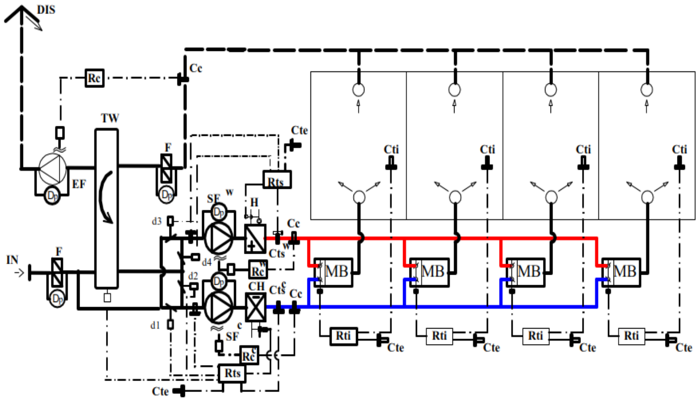

Fig. 2. Schematic of a dual-duct dual-fan ventilation system with individual setting of exhaust air heat recovery for pre-treatment of external air supplied to cold and hot air subsystems.
Key: IN – air intake, d – damper, F – filter, Dp – pressure control, SF – supply air fan, c – cold air, w – hot air, H – heating coil, CH – cooling coil, EF – extract air fan, MB – mixing box, DIS – air discharge, Ct – temperature sensor, e – external air, i – room air, s – supply air, r – air mixture, R – regulator, Rc – pressure regulator, Rt – temperature regulator, Cc – pressure sensor.

Fig. 3. shows a schematic of a new hybrid dual-duct system with extract air recirculation and exhaust air heat recovery. In this technological design solution, the extract air recirculation is individually controlled for the cold and hot air subsystems. Also, energy from exhaust air is used to pre-treat external air distributed into both cold and hot air subsystems. The idea of such a technological solution is to maximise simultaneous usage of both external and exhaust air parameters (temperatures) to set the temperature of hot and cold air, thus minimising primary energy demand for heating and cooling.

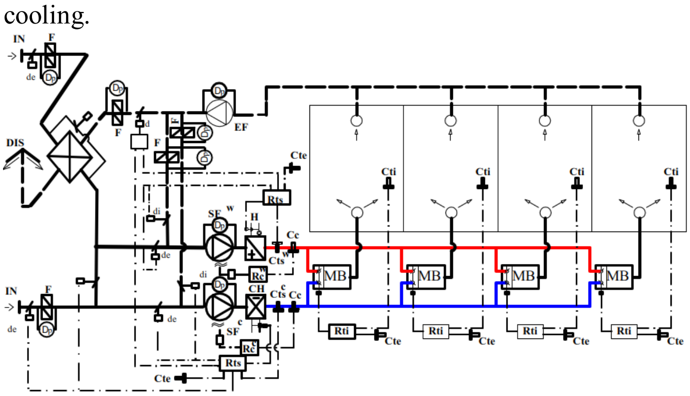

Fig. 3. Schematic of a hybrid dual-duct dual-fan ventilation system with extract air recirculation and heat recovery from exhaust air.
Key: IN – air intake, d – damper, F – filter, Dp – pressure control, SF – supply air fan, c – cold air, w – hot air, H – heating coil, CH – cooling coil, EF – extract air fan, MB – mixing box, DIS – air discharge, Ct – temperature sensor, e – external air, i – room air, s – supply air, r – air mixture, R – regulator, Rc – pressure regulator, Rt – temperature regulator, Cc – pressure sensor.

To illustrate the achievable effects of reducing the energy demand for supply air treatment, we present the results of the full-range dynamic simulation of changes in external air temperature in a yearly cycle of operation of above-described dual-duct systems. Our simulations are carried out at given design conditions and for a summation of thermal loads for all rooms. We present the change of thermal loads as a function of the external air temperature.

3 REDUCTION OF ENERGY DEMAND FOR THERMAL TREATMENT

The t-t_e graphs of the treated air temperature, as a function of the external air temperature, are shown herein to determine the effects of reducing the energy demand for air treatment, as a result of the proposed design solutions of dual-duct ventilation systems. These graphs are based on the following assumptions:
- the constant ventilating airflow;
- the maximum increase in the supply air temperature of 7 K in the room;
- omission of the treated air temperature increase upon passing through a fan;
- changes in the relative heat load of all the rooms, as a function of the external air temperature, as shown in Fig. 4. (a).

Relative heat load q for all the rooms, serviced by a single dual-duct system, is described by eq. (1):

$$q = \Sigma Q_{ci} / \Sigma Q^{max}{}_i \quad (1)$$

where: Q_{ci} denotes the instantaneous heat gains in the i-room (kW) and Q^{maxi} denotes the maximum heat gains in the i-room (kW).

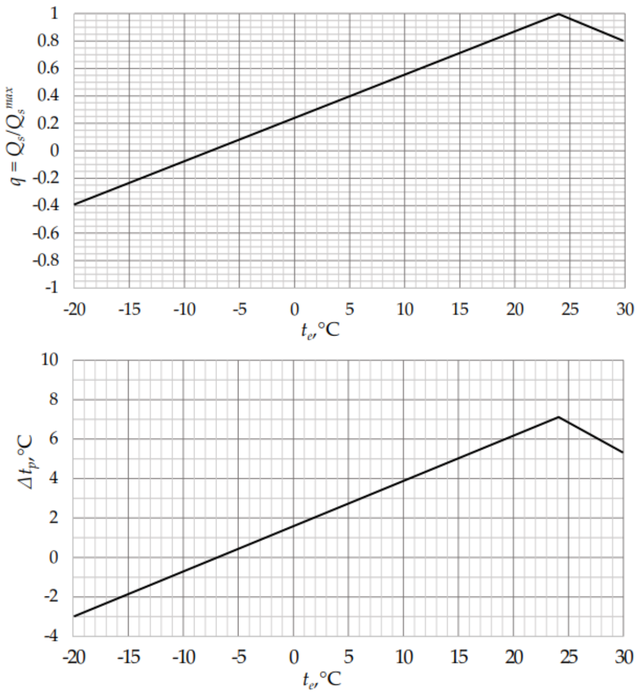

Fig. 4. Functions of external air temperature t_e: relative heat load q of all rooms serviced by dual-duct system; average increment of supply air temperature Δt_p in rooms serviced by dual-duct ventilation system.

Fig. 4. (b) shows the average increase in temperature of the supply air to all the rooms, as a function of the external air temperature, which corresponds to the relative heat load q.

The relationships, presented in Fig. 4.a-b, form the basis for the development of t-t_e graphs showing the variation in the hot and cold air temperature, as a function of the external air temperature. Upon preparing these t-t_e graphs, the room air temperature ensuring thermal comfort is assumed. In the summer period, this corresponds to the room air temperature as a follow-up function of the external air temperature.

4 RESULTS

For relative heat load given in Fig. 4, we have simulated the annual operation of ventilation systems (for schematics of three cases used in simulations, see Fig. 1 - Fig. 3). The results of the dynamic simulations of the annual operation of these systems are presented in Fig. 5. -Fig. 8, respectively. The variations in the following parameters, in the function of external temperature, are shown:
- temperatures of hot and cold airflows,
- internal room air temperatures t_i,
- average supply air temperature t_s,
- temperatures of the mixture of external and recirculating air t_m (in the cold $t^m{}_{e,c}$ and hot air subsystems $t^m{}_{e,w}$),
- temperatures of centrally-treated air in the heat recovery exchanger $t^\eta{}_e$, distributed into the cold $t^\eta{}_{e,c}$ and hot $t^\eta{}_{e,w}$, air subsystems,
- portions of the hot and cold air in the ventilating airflow,
- portions of the external air in the treated cold a_e^c, hot air a_e^w and portions of external air through the bypass of the heat recovery exchanger to the cold air subsystem $a^\eta{}_{e,c}$,
- efficiency of heat recovery from extract air for treatment of hot air η_t^w and cold η_t^c and efficiency of an additional exchanger for heat recovery η_t,
- hot air temperature increase Δt_w in the heating coil and cold air temperature drop Δt_c in the cooling coil.

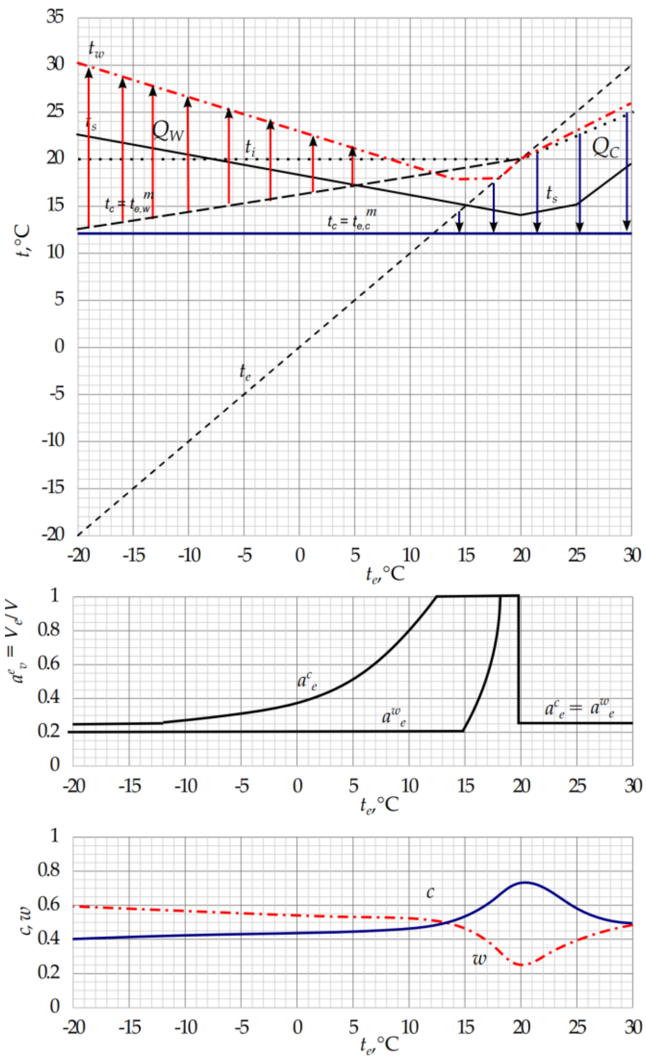

Fig. 5. Results of dynamic simulation of dual-duct system operation, in configuration as shown in Fig. 1, with the minimum potion of external air in the ventilating air $a_e^v = 0.2$ and the relative thermal load of rooms shown in Fig. 4. Functions of external air temperature t_e: variations in temperatures of: hot air t_w and cold air t_c, room air t_i, averaged supply air t_s, mixture of external air and extract air tr; variations in portion of external air in ventilating (a_v^e); variations in portions of hot *w* and cold *c* air.

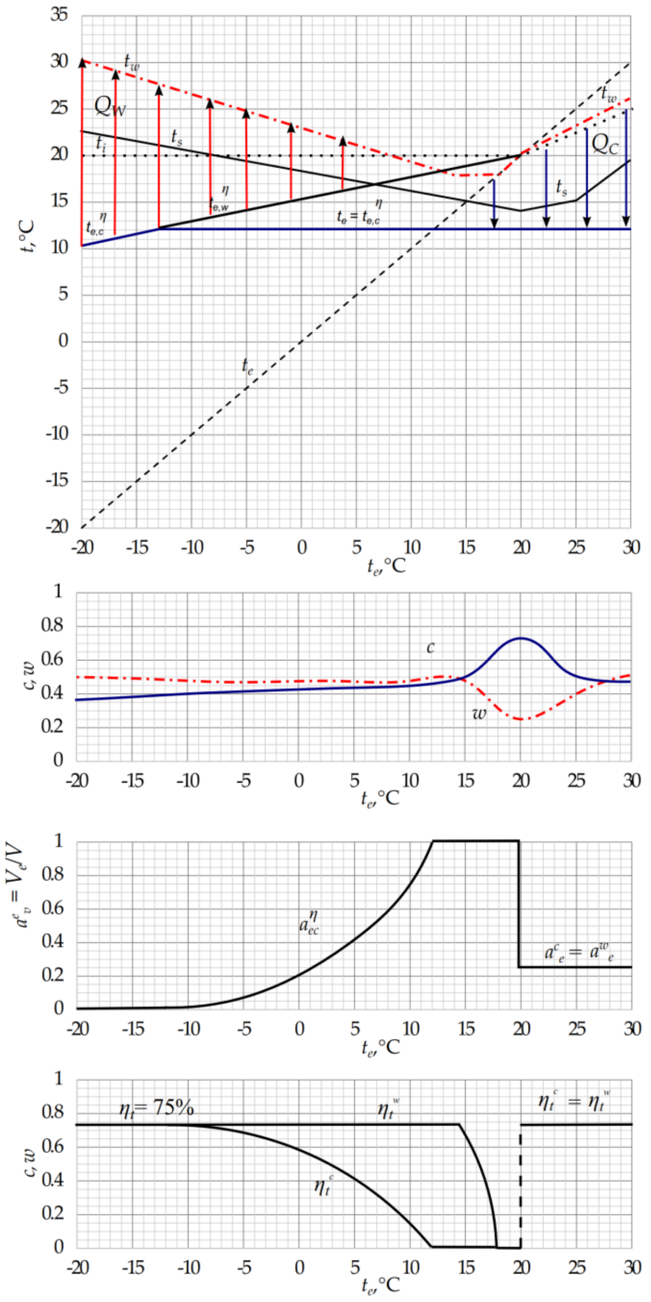

Fig. 6. Results of dynamic simulation of dual-duct system operation, in configuration as shown in Fig. 2, with the maximum thermal efficiency of recovery $\eta_t = 0.75$ and the relative thermal load of rooms shown in Fig. 4. Functions of external air temperature t_e: variations in temperatures of: hot air t_w and cold air t_c, room air t_i, averaged supply air t_s, mixture of external air and extract air tr; variations in portion of external air in ventilating (a_v^e); variations in portions of hot *w* and cold *c* air.

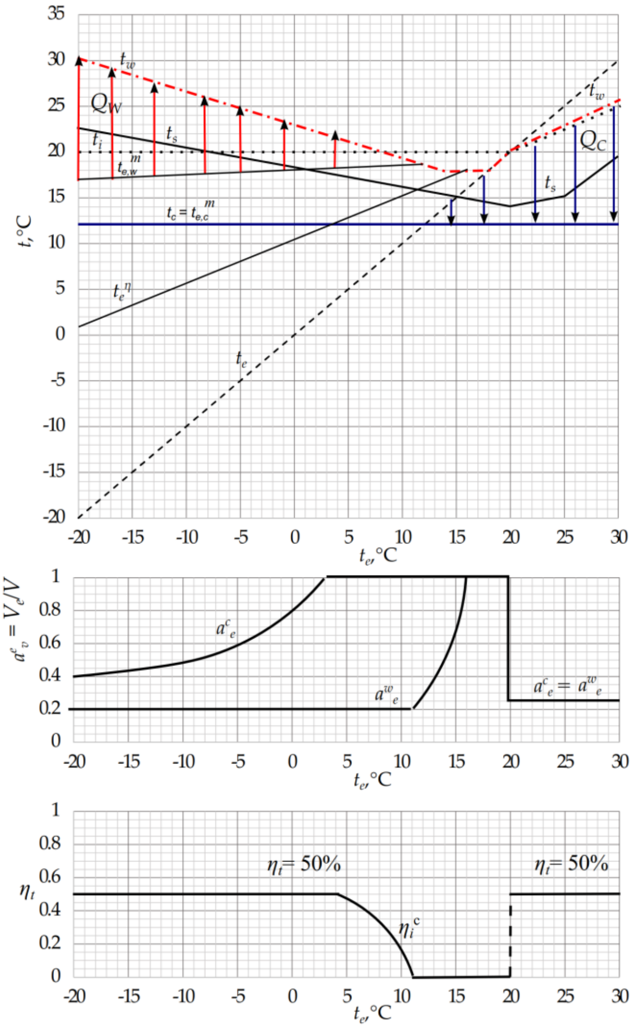

Fig. 7. Results of dynamic simulation of dual-duct system operation, in configuration as shown in Fig. 3, with the minimum potion of external air in the ventilating air $a_e^v = 0.2$, the maximum thermal efficiency of recovery $\eta_t = 0.5$ and the relative thermal load of rooms shown in Fig. 4. Functions of external air temperature t_e: variations in temperatures of: hot air t_w and cold air t_c, room air t_i, averaged supply air t_s, mixture of external air and extract air tr; variations in portion of external air in ventilating (a_v^e); variations in portions of hot w and cold c air.

Fig. 5. - Fig. 7. show variations in temperatures of treated airflows, in the function of external air temperature. Airflows under consideration include: external air (t_e), or mixture of external air (t_e) and circulating water (t_i) Temperature variations occur during thermal treatment processes prior to reaching the cold air ($t^\eta_{e,c}$, $t^m_{e,c}$) and the warm air temperature set-points ($t^\eta_{e,w}$, $t^m_{e,w}$), respectively. We design thermal treatment processes to use both the energy recovered from the exhaust and external airflows and the primary heating and cooling energy. Fields hatched in Fig. 5. - Fig. 7. indicate temperature variations triggered by the primary energy. The temperature increase Δt_w indicates heating of the portion of the ventilating air (namely hot airflow V_w) in the heating coil installed in the hot air system, whereas the temperature decrease Δt_c represents cooling of the portion of the ventilating air (namely cold airflow V_c) in the cooling coil installed in the cold air system.

In addition, Fig. 5. - Fig. 7. show, in the function of external air temperature, portions of the hot and cold air in the ventilating airflow, thermal efficiency of heat recovery in the hot η_t^w and cold air system η_t^c, portions of external air in the hot a_e^w and cold a_e^c airflow, thermal efficiency of heat recovery in additional exchanger η_t and portion of external airflow through the bypass of the heat recovery exchanger (cold air system).

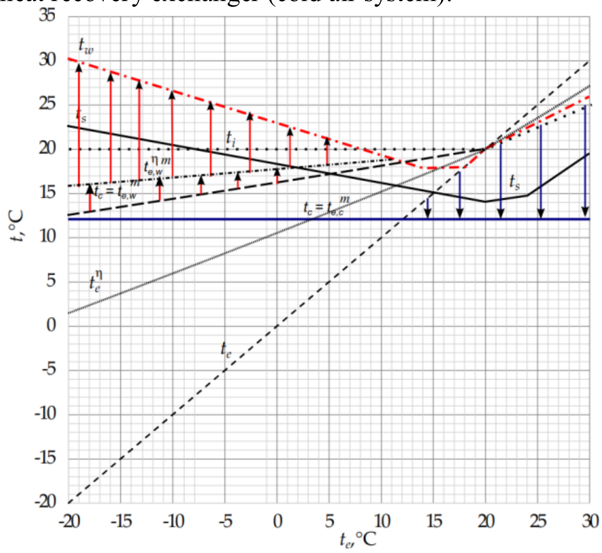

Fig. 8. Results of dynamic simulation of dual-duct system operation, in configuration as shown in Fig. 3, with the minimum potion of external air in the ventilating air $a_e^v = 0.2$, the maximum thermal efficiency of recovery $\eta_t = 0.5$ and the relative thermal load of rooms shown in Fig. 4. Additionally marked is the temperature of pre-treated hot air prior to passing through heating coil ($t^m_{e,w}$).

Fig. 8. shows a graph of the change in the temperature of air treated in the ventilation system shown schematically in Fig. 3. with additionally marked temperature of pre-treated hot air before the heating coil ($t^m_{e,w}$). The hatched field between lines ($t^m_{e,w}$) and ($t^\eta_{e,w}$), represents a decrease in the hot air temperature rise in the heating coil, i.e. reduction of the primary energy demand. This effect is achieved in a dual-duct system with recirculation by adding a heat recovery exchanger to extract energy from the exhaust air. In the summer period, primary energy savings for cooling cold airflow are also achieved and the temperature of the hot air is also lower.

5 CONCLUSIONS

Dual-duct systems have been introduced decades ago to ensure design conditions in multi-room spaces with varying temperature set points and/or different heat loads. The first dual-duct systems were particularly energy-intensive due to technological limitations, control inaccuracies and a limited understanding of annual cycles of operation. However, with the current control and regulation capabilities, the energy demand for air treatment and transport in dual-duct systems can be decreased significantly. The possibility of direct control and regulation of air treatment processes in setting the temperature of hot and cold air, depending on the instantaneous thermal loads in rooms and external air parameters, may lead to: rational use of energy recovered from the exhaust air to adjust the temperature set-points of both hot and cold air and equalization of hot and cold air flows at the inlet to the distribution systems. In advanced and extensive control systems, air treatment in dual-duct systems can also eliminate the processes of simultaneous hot air heating and cold air cooling. In addition, the parallel flow of treated hot and cold air through the heating and cooling coils, rather than in series, reduces the fan static pressure and thus the energy demand for air transport. Also, dual-duct systems allow for individual adjustments of the supply air temperature without local secondary air treatment in each room and additional distribution of heating and cooling medium within the ventilated building. The latter is particularly significant in context of recent controversies regarding refrigerants.

In the paper, we present the fundamental technological design solutions aimed at further reductions of the primary energy demand for the treatment of ventilating air in dual-duct dual-supply-fan ventilation systems. Apart from established design solutions, i.e. extract air recirculation and heat recovery from exhaust air, we propose the new hybrid solution. Our new hybrid system is based on the simultaneous use of extract air recirculation and additional heat recovery from exhaust air.

We used identical thermal loads and operating conditions to simulate the annual operation of dual-duct dual-supply-fan systems under consideration. We present our results in graphs as functions of the external air temperature. Our results include variations: in the temperature of the treated airflow, portions of the hot and cold air in the ventilating airflow, portions of external air in the treated hot and cold air, thermal efficiency of heat recovery from hot and cold airflow.

Our hybrid technological solution results in a significant reduction of the primary energy demand for heating the ventilating airflow. This reduction of primary energy demand may even exceed 30% in the annual cycle of operation.

The simultaneous use of extract air recirculation and heat recovery from the exhaust air ensures the quality improvement of the supplied cold airflow compared to the recirculation only systems. Interestingly, the portion of external air in cold airflow in winter period is higher than the minimum required.

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