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Theoretical Prediction of Longitudinal Heat Conduction Effects on the Efficiency of the Heat Wheel Used for Ventilation in Powerhouse Building “Kjørbo” in Norway

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Abstract

The present study investigates effects of longitudinal heat conduction (LHC) on the heat recovery effectiveness of the heat wheel in the Powerhouse building “Kjørbo”. The effects LHC which are usually ignored in the heat wheel design play a relatively significant role in the heat wheel with high temperature efficiency and short depth in flow direction. The correlation developed by Shah, Kays and London is applied to predict the temperature efficiency and to investigate the impacts of the LHC. Good agreements have been observed between the theoretical predictions obtained from the correlation and experimental data collected from the field test at “Kjørbo”. The influence of the depth of the heat wheel, the airflow rates on the LHC and temperature efficiency were analysed. It was found that the heat wheel has difficulty to achieve a high temperature efficiency (85%) due to the effects of LHC. There is an optimal depth design for heat wheel in the flow direction to recovery maximum thermal energy with low pressure loss with considering the LHC effects. The present study provides preliminary analysis to optimize the heat wheel design and operation with the LHC being taken into account.

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1. Introduction

Heat wheels have been widely used in buildings to recover the energy otherwise wasted in the exhaust air [1]. An accurate prediction of the heat wheel’s thermal performance is highly desirable for heat wheel

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sizing and operating. The design theory of the compact heat exchanger is commonly based on either log-mean temperature difference (LMTD) or ε -NTU method [2]. In both methods, only the transverse heat conduction in the metal walls separating flows is considered and the longitudinal heat conduction (LHC) is neglected. This assumption holds for most heat exchanger applications. However, the effects of the LHC through the wall structure in the flow direction may become quite significant for heat wheels with a short flow length and a high designed effectiveness (>80 %) [3]. The LHC flattens the temperature gradients in the fluid flow direction. Thereafter the LHC reduces the mean outlet temperature of the cold fluid which leads to an effectiveness loss [3]. The ineffectiveness caused by the LHC in the wall could be quite serious, reaching to 20 % of the expected/calculated value [3]. The effects of the LHC have been numerically investigated for heat wheels [3]–[5]. Kroegeer analyzed the LHC challenge for the counter-flow exchanger and he provided an equation to rapidly evaluate the influence of the LHC for balanced flows [6]. A LHC coefficient (λ) was developed to indicate the influence of the LHC on the effectiveness of the heat exchanger through choosing the dimensionless groups [3], [4]. The first analytical closed-form solution to the governing equations taking LHC effect into account for heat wheel was obtained by Skiepko [7]. Bahnke and Howard numerically solved the governing equations of the LHC for the heat wheel with a finite difference method [4]. The results obtained by Bahnke and Howard [4] have been correlated by Shah [5] to simply evaluate the effects of the LHC in the heat wheel.

Nomenclature

$A_{k,t}$	total wall cross-sectional area (m^2)
k_w	thermal conductivity of the matrix material (W/mK)
ε_{cf}	counter-flow heat exchanger effectiveness
C_r^*	total matrix wall heat capacity rate ratio, C_r/C_{min}
NTU	number of heat transfer units

2. The LHC effects on temperature effectiveness

In this paper, the effects of the longitudinal heat conduction in a rotary heat exchanger with balanced flows and counter-flow arrangement are studied. The method developed by Shah and Sekulic [3] is applied to determine the effectiveness of the heat wheel and the influence of the operating conditions and it is briefly introduced below.

The LHC takes place in both fluids and in the separating wall since there is a temperature gradient in the fluid flow direction. The longitudinal heat conduction in a fluid is negligible for most heat exchanger, except for liquid metal and it is not covered in this study. However, the longitudinal heat conduction in the wall may not be negligible for a heat wheel with high NTU and short flow lengths [4]–[7].

The governing equations considering LHC with the boundary conditions have been numerically solved by Bahnke and Howard [4] and their results were correlated by Shah [5] as,

$$\varepsilon = \varepsilon_{cf} \left[1 - \frac{1}{9(C_r^*)^{1.93}} \right] \left(1 - \frac{C_\lambda}{2 - C^*} \right) \quad (1)$$

Where,

$$C_\lambda = \frac{1}{1 + NTU_o(1 + \lambda\Phi)/(1 + \lambda NTU_o)} - \frac{1}{1 + NTU_o} \tag{2}$$

Based on Ref [3] and for $NTU \geq 3$

$$\Phi \approx \left(\frac{\lambda NTU_o}{1 + \lambda NTU_o} \right)^{1/2} \tag{3}$$

$$\lambda = \frac{k_w A_k}{LC_{min}} \tag{4}$$

λ is defined as a dimensionless LHC parameter which refers to a ratio of longitudinal wall heat conduction per unit length to the heat capacity rate of the fluid and per unit temperature difference [3]. The higher value of this LHC parameter, the higher LHC loss is in the heat exchangers.

For balanced flow in counter-flow heat exchanger, ϵ_{cf} can be expressed as [2],

$$\epsilon_{cf} = \frac{NTU_o}{1 + NTU_o} \tag{5}$$

Bahnke and Howard [4] determined the effects of the LHC and effectiveness of the heat wheel over the ranges of the dimensionless parameters: $0.9 \leq C^* \leq 1$, $1 \leq NTU_o \leq 100$, $1 \leq C_r^* \leq \infty$, $0.01 \leq \lambda \leq 0.32$.

3. Results and discussion

Figure 1. shows the working diagram of the aluminium heat wheel mounted at Powerhouse Kjørbo (for block 4) in Norway. The balanced mass flow operation is studied (the unbalanced rate is less than 0.6%). The designed nominal airflow rate for the heat wheel is $25000 \text{ m}^3/\text{h}$, however, the maximum airflow rate in operation is $15000 \text{ m}^3/\text{h}$. Consequently, the heat wheel is supposed to operate with high effectiveness due to the oversized exchanger surface area.

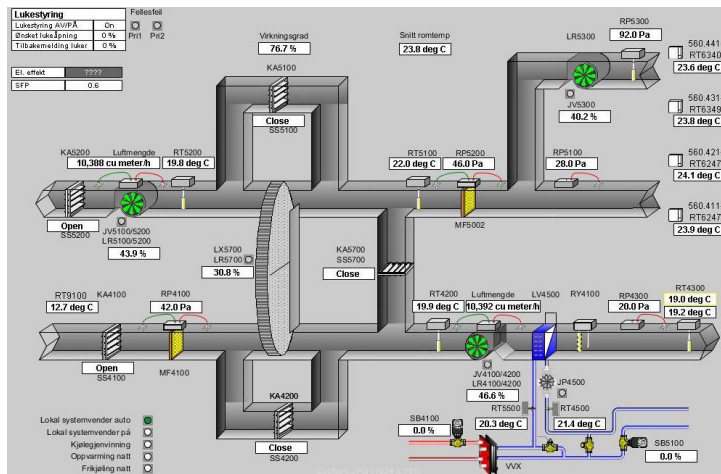


Figure 1. Operating diagram of the heat wheel mounted at powerhouse Kjørbo

The specifications of the heat wheel are given in Table 1.

Table 1. Specifications of the heat wheel in the powerhouse Kjørbo

Parameters	Units	Values
Diameter of the heat wheel (D)	mm	2495
Diameter of the boss (d)	mm	180
Corrugation period (P)	mm	4.3
Channel pitch (H)	mm	1.4
Heat exchanger flow length (L)	mm	200
Wall thickness (δ)	mm	0.08
Rotary speed at full power of motor (N)	rpm	10

The corrugation of the heat wheel is assumed to be an ideal sine function. The effectiveness-NTU method is used to calculate ϵ_{cf} as depicted in Eq. (5). NTU is defined as $NTU = \frac{UA}{C_{min}}$. The UA for the heat wheel can be determined based on the information of different wall surfaces in Ref. [3]. The transverse wall heat conduction is neglected in the process of determining UA due to the thin wall thickness. Using the presented mathematical model and information of the heat wheel, the effectiveness is predicted for the heat wheel with or without including the effects of the LHC. The experimental effectiveness is also available through monitoring the inlet and outlet temperatures and airflow rates close to the heat wheel. The theoretical prediction of sensible effectiveness and experimental data are presented in Figure 2. The effectiveness discrepancies between theoretical prediction and experimental data are presented in Figure 2 as well. Figure 2. proves that the theoretical effectiveness prediction considering the LHC effect agrees with the experimental results very well (under 6 % for various airflow rates and rotary speeds). The effectiveness-NTU method without considering the LHC effect tends to greatly over-predict the effectiveness (ranging from 5 % to 20 %). For most operating airflow rates (around $5000\text{ m}^3/h$), the effectiveness is over-predicted by 20 % without considering the LHC. Obviously, the effect of the LHC cannot be ignored in this case. It can be also found that the effect of the LHC on the effectiveness is smaller for increasing airflow rates which gives the decreasing effectiveness.

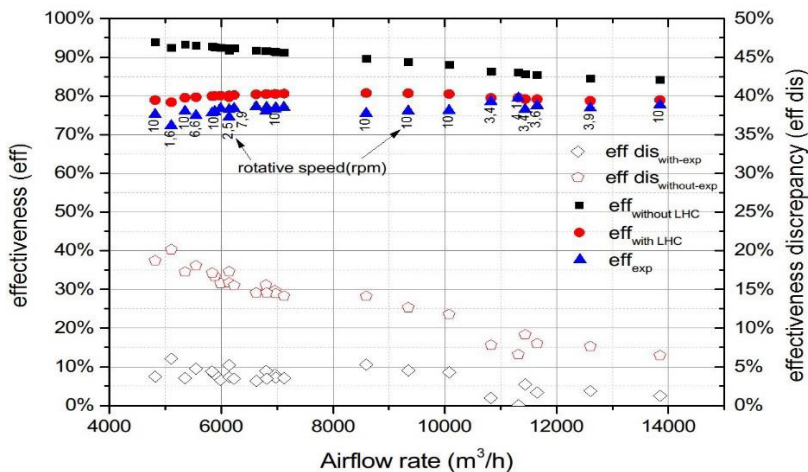


Figure 2. Theoretical and experimental effectiveness of the heat wheel for various airflow rates and rotary speed

Based on the definition of the LHC parameter in Eq. (4), increasing the flow length or decreasing the total wall cross-sectional area results in a lower value of the LHC parameter. The influence of the dimension of the heat wheel is analyzed in this paper keeping total heat transfer area as a constant (1045 m^2). When the air flow length (wheel width) is increased, the total front surface area will decrease. As a result, the effect of LHC tends to be reduced because of the decreased LHC parameter as shown in Figure 3. If the flow length of the heat wheel is doubled, the effect of the LHC on the effectiveness loss could be neglected. However, the increased air velocity and flow length will increase the pressure drop through the heat wheel. Therefore, an optimal dimension design exists considering the effect of the LHC on effectiveness loss and pressure drop.

The influence of airflow rates on the LHC are examined based on the theoretical effectiveness prediction model with the LHC effect. Their influence are shown in Figure 4. It can be observed in Figure 4, at low airflow rates ($5000\text{-}1000 \text{ m}^3/h$), the effectiveness of the heat wheel decreases with decreasing airflow rates which has opposite trend with the calculated effectiveness without considering the LHC. The effectiveness of the heat wheel decreases with increasing airflow rates when the airflow rates are higher than $10000 \text{ m}^3/h$ regardless of considering the LHC effect. The trends indicate that the LHC plays a key role for low airflow rates. The low airflow rate cannot provide the expected effectiveness. In fact, it is found that the heat wheel has difficulty to provide temperature efficiency higher than 85%. To reduce the LHC effect for low airflow rates and maintain a high effectiveness operation, perforated high thermal conductivity plates [8], wire screens or low thermal conductivity spacers for instance plastic may be recommended [3].

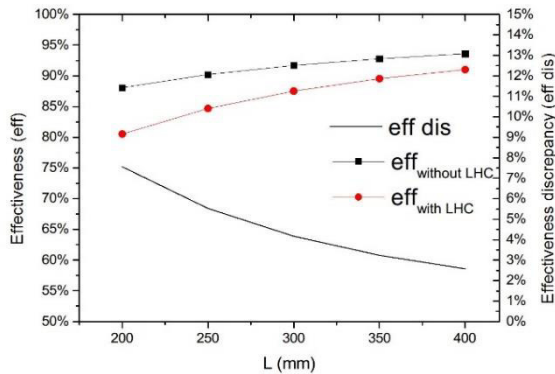


Figure 3. Influence of flow length on the LHC effect with total heat transfer area 1045 m^2 , rotary speed 10 rpm, and airflow rate $10000 \text{ m}^3/h$

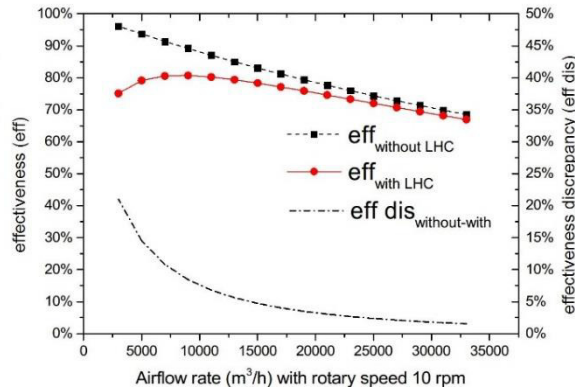


Figure 4. Influence of airflow on the LHC effect with rotary speed 10 rpm and flow length 200 mm.

Conclusions

The effectiveness of a heat wheel at the powerhouse Kjørbo are predicted with considering the LHC effect using the presented prediction model. Good agreements between the theoretical results and data are obtained. The unexpected low temperature efficiency of the heat wheel is confirmed as a result of the LHC effects. The influence of heat wheel design depth, airflow rates on the LHC effect and temperature efficiency are analysed. The high temperature efficiency (85%) is difficult to obtain due to the LHC. An optimal dimension design need to be further studied with considering the reduction of LHC effect and pressure drop. The perforated high thermal conductivity plates, wire screen or plastic walls are recommended for heat wheel construction to reduce the LHC effect.

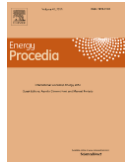
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Biography



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