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# Effects of Multi-Stage Sudden Expanded Channel on Heat Transfer and Flow in Earth-Air Heat Exchanger

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**Abstract:** *The thermal-hydraulic performance of a multi-stage sudden expanded channel design for Earth-Air Heat Exchanger (EAHE) application is explored in this study. The computational analysis is based on a horizontal cross-section model composed of a series of large (diameter 0.1 m) and small (diameter 0.05 m) cylindrical sections of length 0.5 m each. The study compares the heat transfer and pressure drop characteristics of the different Reynolds number for inlet air temperature at 50°C and surface temperature at 30°C at a velocity of 2.98 m/s. The results show that the multi-stage sudden expansion configuration can improve heat transfer performance considerably while introducing some pressure loss, which is more than that of the basic sudden expansion configuration. Optimum design configurations are analyzed by considering the thermal performance enhancement ratio and hydraulic performance penalty ratio.*

**Keywords:** *Earth-Air Heat Exchanger, Sudden Expansion, Heat Transfer Enhancement, Pressure Drop, Multi-Stage Design.*

## 1. Introduction

Earth-to-air heat exchangers (EAHE) are considered a renewable research technology that does not consume energy [1]. The concept is based on a simple principle: burying a pipe with good thermal conductivity, such as steel, PVC, or other materials, at a certain depth, where the underground temperature remains relatively constant and is not affected by seasonal outdoor variations [2]. Air is commonly used as the working fluid, through which heat is transferred to and from the pipe during its passage. The soil acts as a heat sink (storage reservoir) or a heat source due to its high thermal energy storage capacity [3].

Vikas et al. (2009, 2010) [4,5] conducted experimental and numerical studies to investigate the effect of air velocity on the performance of the EAHE system, and their results showed that increasing the air velocity improved the air temperature during both summer and winter seasons. Sehli et al. studied a one-dimensional numerical model to evaluate the performance of an EAHE system installed at different depths in southern Algeria and concluded that these systems can be used to reduce energy consumption; however, the systems alone are insufficient to achieve thermal comfort conditions [6]. Woodson et al. carried out an experimental study to evaluate the performance of an EAHE system during the hottest day in Burkina Faso, using a pipe with a length of 25 m and a diameter of 0.125 m buried at a depth of 1.5 m, where the outdoor air temperature reached 39°C, and their results indicated that the system reduced the air temperature by 7.6°C compared with the outdoor air temperature [7]. Bansal et al., 2009; Bansal et al., found Passive building heating and cooling systems use the relatively constant ground temperatures to precondition the ventilation air through the relatively simple Earth-Air Heat Exchanger (EAHE), which has increasingly emerged as an important technology [8,9]. The performance of EAHE systems is highly dependent on the heat transfer characteristics of the air passing through the pipes that are buried in the soil, as well as the pressure drop, which dictates fan energy consumption [10] .

discovered that Typical EAHE designs use pipes of constant diameter and there is limited heat transfer performance. In recent years, attention has been paid to the geometric modifications to improve the thermal exchange at a non-impeditive increase in the pumping power [11]. Some of these changes are found to have potential in enhancing flow mixing and convective heat transfer coefficients: Sudden expansion geometries [12,13 ] noticed that the flow separation and reattachment that occurs downstream of sudden expansions generate recirculation zones which increases turbulent mixing and heat transfer) , But they have penalties associated with them in pressure that need to be considered for real-world applications. The multi-stage sudden expansion design studied in this work seeks to do just this by spread over multiple stages, possibly yielding greater heat transfer enhancement in exchange for less pressure drop penalties [14].

In the present study, computational analysis of the thermal-hydraulic performance of a multi-stage sudden expanded channel design for EAHE applications is described. The geometry is composed of alternate large and small diameter cylindrical sections, the size of which are chosen based on the size of practical EAHE configurations. The study compares the performance enhancement of the Nusselt number, characteristics of the friction factor, and overall performance of the Nusselt number for various Reynolds numbers.

## 2. Methodology

### 2.1 Geometry and Computational Domain

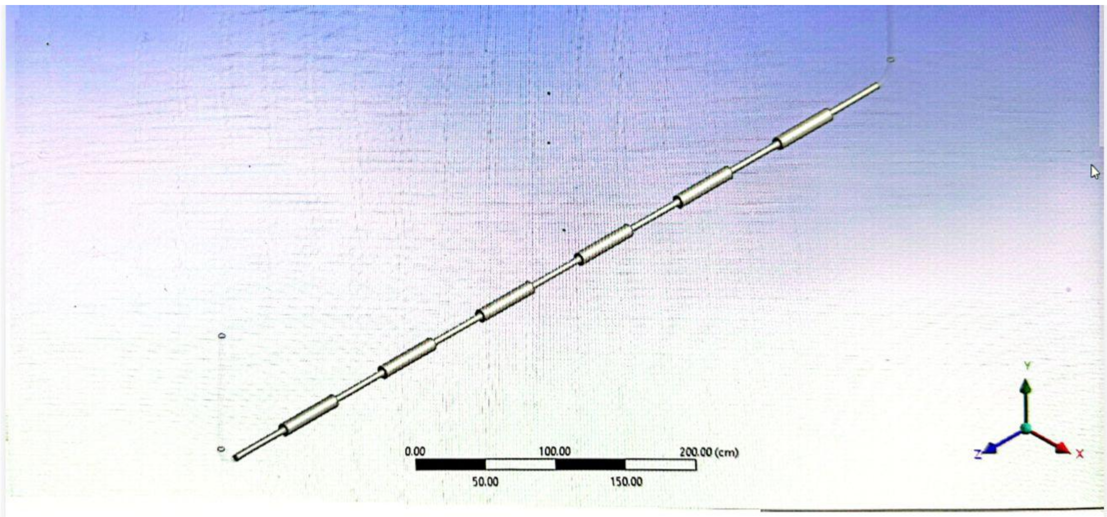


Figure 1: 3D Computational domain and geometry of the multi-stage sudden expanded EAHE.

The computational domain represents a three-dimensional horizontal section model of a multi-stage EAHE, consisting of alternating large and small diameter cylindrical sections. Each cylindrical section has a length of 0.5 m. The large diameter sections measure 0.1 m (10 cm), while the small diameter sections measure 0.05 m (5 cm). The multi-stage configuration creates repeated sudden expansions and contractions along the flow path.

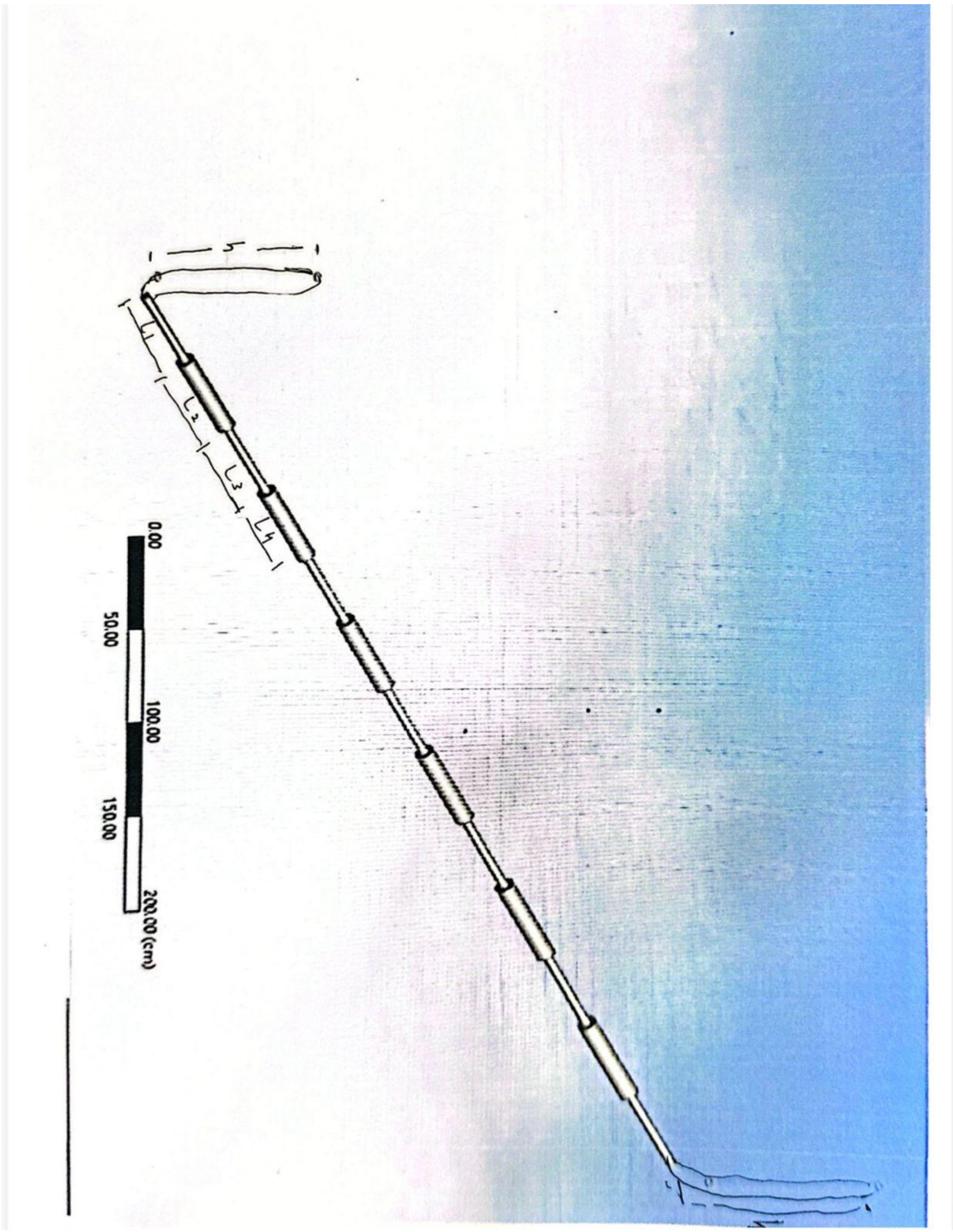


Figure 2: Schematic diagram showing the geometrical dimensions and layout of the sudden expansion stages.

The sudden expansion stages are sequenced as shown in Figure 2, such that the flow enters through a small diameter stage, expands to a large diameter stage and then contracts back to a small diameter stage prior to the next expansion stage. This is an alternating geometry which is expected to improve convective heat transfer due to repeated flow separation, recirculation and reattachment.

### 2.2 Boundary Conditions

The numerical simulations were carried out under the following boundary conditions:

Inlet air temperature: 50°C

Heat transfer coefficient, h: 0.88 W/m².K (h=constant all over the surface)

Inlet velocity: 2.98 m/s

Working fluid: Air with temperature-dependent properties

The range of Reynolds number was determined using the hydraulic diameter of the small sections which are the limiting flow sections. The velocity 2.98 m/s was chosen as a representative for EAHE applications, which is representative of typical ventilation flow rates.

### 2.3 Governing Equations and Numerical Method

The finite volume method was used to solve the governing equations for steady, incompressible turbulent flow and heat transfer. A grid independence study was conducted using three different mesh sizes to ensure that the numerical results are independent of the grid resolution. The continuity, momentum and energy equations are presented in a text friendly format as follows:

Continuity equation:

$$\partial u_i / \partial x_i = 0$$

Momentum equation (Reynolds-Averaged Navier-Stokes):

$$\partial(\rho u_i u_j)/ \partial x_j = -\partial p/(\partial x_i) + \partial/(\partial x_j) [ \mu ((\partial u_i)/(\partial x_j) + (\partial u_j)/(\partial x_i)) - \rho * (u_i^{\prime} u_j^{\prime})] )$$

where the overbar on $u'_i u'_j$ denotes the time-averaged Reynolds stress tensor.

Energy equation:

$$\partial(\rho u_j T)/ \partial x_j = \partial/(\partial x_j) [ ((\mu/(Pr + \mu_t))/Pr_t)* (\partial T/(\partial x_j))] )$$

The turbulent Reynolds stresses and heat fluxes were modeled using the Realizable k-ε turbulence model with enhanced wall treatment, validated against established correlations for sudden expansion flows.

### 2.4 Performance Parameters

The thermal performance was evaluated using the Nusselt number, defined in text format as:

$$Nu = (h * D_h) / k$$

where h is the convective heat transfer coefficient, $D_h$ is the hydraulic diameter, and k is the thermal conductivity of air.

The friction factor was calculated using:

$$f = \Delta P / [ (L / D_h) * (\rho * V^2 / 2) ]$$

where ΔP is the pressure drop, L is the flow length, ρ is the air density, and V is the average velocity.

The thermal performance enhancement ratio was defined as $Nu / Nu_{ref}$, where $Nu_{ref}$ represents the Nusselt number for a reference constant-diameter channel with the same hydraulic diameter ($D_h = 0.05$ m) and under identical flow conditions. Similarly, the hydraulic performance penalty ratio was defined as $f / f_{ref}$, where $f_{ref}$ is the friction factor for the reference channel.

## 3. Results and Discussion

### 3.1 Heat Transfer Enhancement

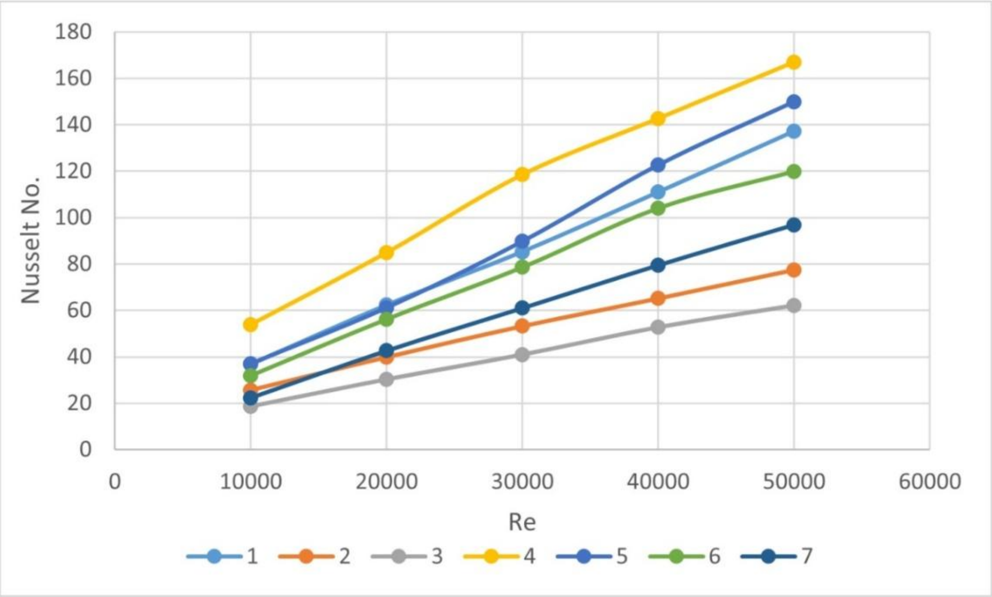


Figure 3: Variation of the Nusselt number (Nu) versus Reynolds number (Re) for different stages.

In Figure 3, the variation of Nusselt number with Reynolds number for the different stages of the multi-stage sudden expanded EAHE is presented. The results show the Nusselt number is also found to significantly rise with increase in Reynolds number in all the stages of the experiment, which is in agreement with the heat transfer behavior of turbulent flow. The Nusselt numbers on the multi-stage configuration are clearly larger than reference numbers found for channels with constant diameter [15].

The variation of Nusselt number, from stage to stage, is indicative of the gradual development of flow in the sudden expansion geometry. The larger Nusselt numbers in the region immediately downstream from the sudden expansions are due to flow separation and reattachment, which result in increased temperature gradients near the wall and mixing within the flow. This result is similar to the conclusions of Chieng and Launder who found higher heat transfer downstream of sudden pipe expansions in the reattachment region.

There are several mechanisms which can account for the improvement in heat transfer:

Recirculation zones are generated at the sudden expansion where turbulent mixing occurs.

In the reattachment region the velocity gradients are large and the wall shear stress is higher.

Repeated expansion and contraction do not allow for the complete re-establishment of developed flow, and thus heat transfer is enhanced along the channel.

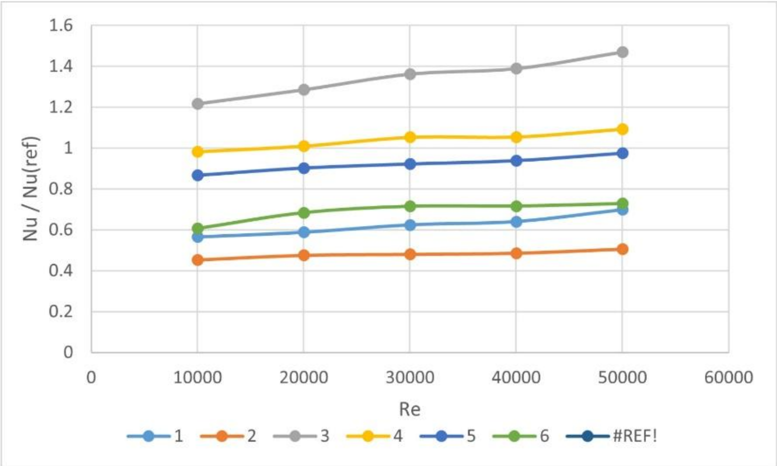


Figure 4: Thermal performance enhancement ratio (Nu / Nu_ref) plotted against Reynolds

number.

Figure 4 shows the enhancement ratio for thermal performance as a function of Reynolds number. The enhancement ratio is found to be greater than unity in all cases, thus demonstrating that the multi stage sudden expansion design offers better heat transfer than reference channels. The enhancement ratio shows a negative trend with increasing Reynolds number, indicating that the relative improvement of the sudden expansion geometry is more significant at lower flow rates.

The enhancement ratio obtained in the range of Reynolds number investigated was approximately 2.0-3.0, suggesting that the multi-stage design can double or triple the EAHE heat transfer performance compared to that of the conventional EAHE designs. This significant improvement may allow for smaller heat exchanger designs or provide for greater performance efficiency from a specific installation area.

For EAHE applications, the temperature difference between the air and the surrounding soil is the main factor that determines the heat exchange process and the thermal performance enhancement is more pronounced. Reduced pipe length or better outlet air temperature conditioning can be achieved due to the enhanced heat transfer coefficients which can be obtained.

### 3.2 Pressure Drop Characteristics

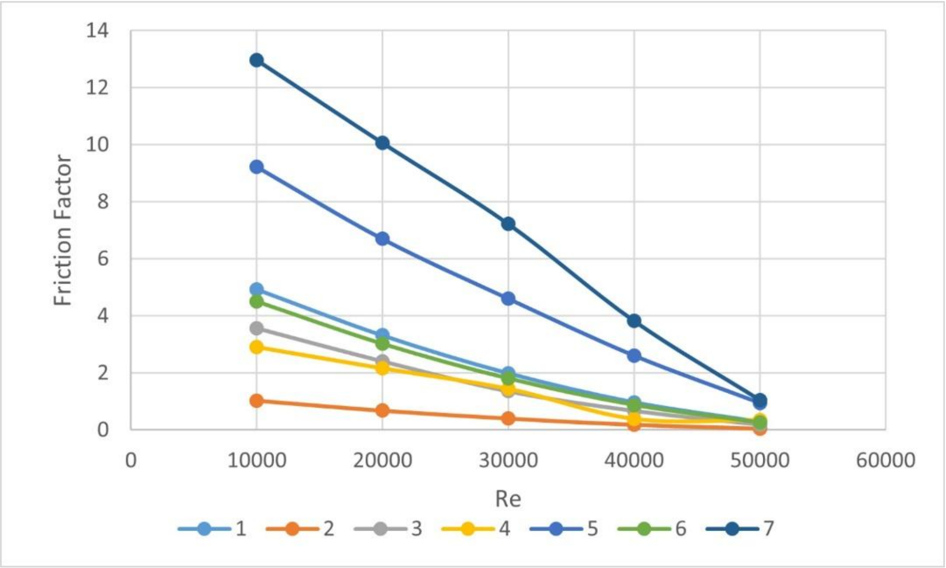


Figure 5: Friction factor (f) variation against Reynolds number for the studied design configurations.

The friction factor is shown as a function of the Reynolds number for the multi-stage sudden expanded EAHE configurations in Figure 5. The characteristic behaviour of the friction factor with the increase of Reynolds number, which is common in turbulent flow in ducts, was observed. These values are significantly greater than those for smooth constant diameter channels however, due to the extra pressure loss from the sudden expansions and contractions.

The friction factors for the multi-stage design are also higher than the reference values, indicating that the pressure drop penalty of the geometric changes is higher. This pressure penalty is caused by:

2. Create losses at sudden expansions and contractions.

2. Greater turbulent dissipation in the recirculation zones.

3. Increased wall shear stress in the reattachment regions.

The results for the friction factor are comparable with those of Amanowicz, which indicated higher pressure drop in EAHE systems having geometric changes. The two higher friction factors are the basic design compromise that results from a better heat exchanger – the more heat the exchanger can get from a fluid, the more pumping power it will require.

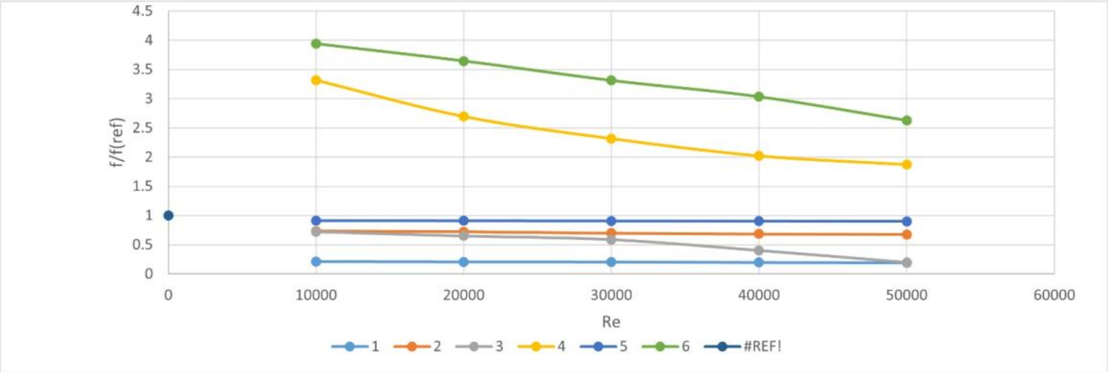


Figure 6: Hydraulic performance penalty ratio (f / f_ref) versus Reynolds number demonstrating pressure drop characteristics.

The hydraulic performance penalty ratio is plotted against Reynolds number as shown in figure 6. The penalty ratio is the ratio of the increase in the friction factor to the reference channel. The results show that the penalty of the multi-stage sudden expansion design is very high, especially at lower Reynolds numbers.

As Reynolds number increases, the hydraulic penalty ratio will decrease, indicating that the loss in pressure drop will be less severe at higher flow velocities. The relative importance of the form losses vs. the frictional losses is the reason for this behavior; as the Reynolds number increases the frictional losses in the reference channel increase and hence the additional form losses of the sudden expansions are less significant.

For practical EAHE applications, the pressure drop characteristics for the multi-stage design need to be carefully considered. The additional heat transfer is good, but the additional pressure drop can necessitate larger fans or more energy use to compensate for the benefits of the better heat exchange, so this may not offset the energy benefit from the heat exchange.

### 3.3 Overall Performance Assessment

Multi-stage EAHE systems are studied and the analysis of both the enhancement in heat transfer and the penalty in pressure drop provides important clues to the practical application of multi-stage EAHE systems. The thermal performance enhancement ratio (Figure 4) and hydraulic penalty ratio (Figure 6) illustrate the basic trade-off between enhancing thermal performance and increasing hydraulic penalties in heat exchanger design.

The multi-stage sudden expansion design provides significant enhancement of heat transfer, with values of Nu/Nu_ref as large as 2.5 – 3.0 for lower Reynolds numbers. This improvement comes with high pressure penalties however, ranging from 2.0 to 4.0, in terms of f/f_ref. The multi-stage design's optimum operating conditions are influenced by the significance of thermal performance versus pumping power consumption for the particular application.

The pressure drop for EAHE applications needs to be balanced with the enhanced heat transfer. The increase in fan energy consumption due to the higher pressure loss needs to be considered in relation to the savings in energy from better heat exchange. The enhancement ratio is more favorable as compared to the penalty ratio at lower Reynolds numbers suggesting that the multi-stage design may prove more advantageous at moderate flow rates.

Advantages of multi-stage over single stage sudden expansion designs is the spreading of the flow disruption at multiple stages. Such a strategy will keep the developed flow from completely re-establishing between expansions, thereby extending the mixing and heat transfer from the developed flow throughout the length of the channel. These expansions and contractions produce multiple recirculation regions that constantly increase the amount of thermal transfer, hence increasing the effective heat transfer coefficient.

### 3.4 Practical implications for EAHE design

This study has a number of practical implications for the design and operation of EAHE systems:

2. Better Thermal Performance: The multi-stage sudden expansion design has better heat transfer performance than EAHE systems with constant diameter pipe, which could allow shorter pipe length and/or better outlet air temperature conditioning.

Multi-stage design considerations: Pressure drop, system design and fan selection need to be considered. The extra power required for pumping needs to be considered in the energy performance calculations.

Optimal Operating Range: The enhancement-to-penalty ratio is higher in lower Reynolds number, indicating that the Multi-Stage design could be more effective for applications that involve moderate airflow requirement.

Number of Stages Optimization: The number of stages is a design variable that can be optimized depending on the specific applications. Further stages offer further improvements (with less and more pressure penalties).

5. Geometric Optimization: The dimensions of the large and small parts (0.1 m and 0.05 m used in this study) is one possible geometry. The diameter ratio and stage length may be changed and optimized in order to further maximize the enhancement/penalty ratio.

Additionally, the temperature profile of the ground is determined by climatic conditions and soil properties, and this also affects the thermal performance of EAHE systems. EAHE systems make use of the thermal potential of the stable ground temperatures at moderate depths (generally 1–3 m deep), which are normally measured below the ground surface [16]. A multi-stage design improves heat transfer, which helps to use this heat potential efficiently.

## 4. Conclusions

The study reveals that the multi-stage sudden expanded channel can achieve the heat transfer enhancement ratios of about 2.0–3.0, which is significantly higher than conventional constant-diameter channel. This improvement is believed to be a result of separation and reattaching of the flow at each expansion stage which creates turbulent mixing, and enhances the convective heat transfer coefficient. On the other hand, there is a significant penalty in pressure drop, with friction factor penalty ratios of 2.0 to 4.0. The enhancement-to-penalty ratio is even better at low Reynolds numbers so the design would be especially well suited to designs with moderate flow rates. Practical advantages include the possibility of lowering pipe lengths or outlet air temperature, and a greater head loss will have to be incorporated into the system design. In addition, the repeated staged configuration does not allow the flow to attain the full developed condition, which means that the very same configuration along the entire channel length causes enhancement of the heat transfer.

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