INVESTIGATION IN CRITICAL RADIUS OF THERMAL INSULATION FOR VERTICAL PIPES

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Abstract. Thermal insulation of pipelines finds application across various industries, including agricultural technologies. The energy efficiency hinges on minimizing heat losses. The task is primarily achieved through effective heat insulation. Decentralized ventilation systems prove to be efficient in rural low-rise constructions. Among these, regenerative ventilators like Blauberg Vento/Vents TwinFresh stand out. There exists a goal to enhance their operational efficiency, which involves ongoing investigation into heat recovery processes within their thin ducts. Improving the insulation of the experimental setup leads to a reduction in experimental uncertainty. Also, a new gas exchange camera for CO_2 exchange in plants requires very low uncertainty of airflow measurements requiring very high precision of air density measurement. However, heat losses can influence the air temperature deviation in a flow meter. However, within the realm of heat transfer literature, the concept of the critical insulation radius is stated. Increasing the insulation radius beyond a certain point might diminish its efficacy due to outer surface development. Theoretical assumptions posit a constant heat transfer coefficient for the outer surface. Previously, we analysed the critical radius of horizontal cylinder pipes. This study deals with laminar convective flow around the outer vertical cylindrical insulation surface. Employing a formula considering the Grashof number, the average heat transfer coefficient is analysed. The results indicate that increasing insulation thickness reduces the surface temperature and the heat transfer coefficient such as for vertical pipes. An analysis of the thermal resistance function concerning the ratio of outer to inner diameters, and its derivative, was conducted. The asymptotic increase in the thermal resistance was found. This fully disproves the critical radius concept opening new perspectives on energy efficiency and thermotechnical research precision.

Keywords: energy efficiency; critical insulation radius; heat transfer coefficient; Nusselt number; vertical cylinder.

Introduction

One of the common problems in the construction industry is heat loss. It also occurs in other fields of science and technology, including agriculture [1-5]. The concept of heat loss is closely related to the thermal characteristics of insulation materials used, including insulation thickness [6-8]. Thermal insulation of pipelines has various industrial applications, including in agricultural technologies. The main objective is to minimize heat losses to increase energy efficiency. Effective heat insulation is the key to achieving this task. While the notion of perfect insulation [9] holds value theoretically, it remains unattainable in practical applications. Examination of building insulation [10-14] may reveal substantial external dimensions necessary for effective insulation. Conversely, thermal insulation requirements for optical elements [15] and pipes [16-18] often involve smaller dimensions, yet still prove efficient in all scenarios.

An effective solution for maintaining optimal microclimate conditions in rural buildings is the use of decentralized ventilation systems [19-22]. This kind of system boasts numerous advantages, occupying minimal space and minimizing interference with the building interior. One notable device is the regenerative ventilator, such as the TwinFresh by Vents or the Vento by Blauberg, which alternates between supply and exhaust cycles. During summer, this device can outperform recuperative systems installed on vertically greened walls by harnessing cooling effects [23] and sanitation capabilities [24-26] without the significant air recirculation caused by vegetation. Moreover, this setup provides cost-effective protection against solar radiation in combination with green roofs or terraces [27-28]. Furthermore, the efficiency of air distribution significantly impacts energy performance [29-33], particularly in variable air volume ventilation [34-39]. Unlike recuperative systems, the decentralized device does not operate the neighbouring air inlet and outlet simultaneously, thereby preventing the exhausting of the inlet air. Improving the efficiency of such devices, as evidenced in studies [19; 22], hinges on enhancing the performance of the regenerative heat exchanger.

During preparation of the experimental setup, there arose a need to calibrate thermocouples. For this, a calibration setup was created, which required an accurate determination of the thickness of vertical thermal insulation. Improving the insulation of the experimental setup can reduce experimental

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uncertainty. Additionally, a new gas exchange camera for CO_2 exchange in plants requires very precise air density measurements, which can be influenced by heat losses that affect the air temperature deviation in a flow meter.

In previous studies, the theory of the critical radius of horizontal thermal insulation was debunked [40; 41]. The objective of the study is to verify the existence of a critical radius for vertical thermal insulation. The object of this study is vertical thermally insulated cylindrical bodies. The research subject is the heat transfer process from a heated or cooled medium inside the vertical cylinder to the external environment surrounding it.

Materials and methods

Let us consider a vertical thermal insulated cylinder, heated or cooled. Around it, a thermal-gravitation flow will appear. The height of the cylinder is h, m. The outer diameter is d, m. For the Nusselt number Nu_h, there is an equation [42].

$$Nu_h = \alpha \cdot d/\lambda_{air} = 0.67 \cdot Pr_{\mathrm{ext}}^{1/4} \cdot Gr_h^{1/4}, \tag{1}$$

where α – heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$;
λ_{air} – thermal conductivity of air, $W \cdot m^{-1} \cdot K^{-1}$;
$Gr_h = g \cdot (1/T_{ext}) \cdot h^3 \cdot (T_{surf} - T_{ext})/\nu^2$ – Grashof number;
T_{surf} , T_{ext} – temperature of the outer surface and external air, K;
g – gravity acceleration, $m \cdot s^{-2}$;
Pr_{ext} – external Prandtl number.

After transforming equation (1), $W \cdot m^{-2} \cdot K^{-1}$,

$$\alpha = 0.67 \cdot Pr_{ext}^{1/4} \cdot \left(g \cdot \beta \cdot h^3 \cdot (T_{surf} - T_{ext})/\nu^2\right)^{1/4} \cdot \lambda_{air}/d. \tag{2}$$

The linear thermal resistance, $m \cdot K \cdot W^{-1}$, is

$$R_{\ell} = R_{\ell 0} + \ln(d/d_0)/(2 \cdot \pi \cdot \lambda_{ins}) + 1/(\pi \cdot d \cdot \alpha), \tag{3}$$

where $R_{\ell o}$ – linear resistance of the inner side, $m \cdot K \cdot W^{-1}$;
λ_{ins} – thermal conductivity of the insulation material, $W \cdot m^{-1} \cdot K^{-1}$;
d_0 – internal diameter of the insulation, m.

By the heat transfer equation [43; 44] using (3):

$$\left(T_{int} - T_{surf}\right)^4 = $$
$$= (0.335 \cdot \lambda_{air}/\lambda_{ins} \cdot ((R_{\ell 0} + \ln(d/d_0))/(2 \cdot \pi \cdot \lambda_{ins}))^4 \cdot Pr_{ext} \cdot g \cdot h^3/\nu^2 \cdot \left(T_{surf} - T_{ext}\right)^5/T_{ext} \tag{4}$$

Let us use the following parameters. Relative temperature differences between the inside and outside insulation surfaces related to the outer air temperature:

$$\Delta T_{int} = (T_{int} - T_{ext})/T_{ext} > 0; \ \Delta T_{surf} = (T_{surf} - T_{ext})/T_{ext} > 0. \tag{5}$$

It is strictly positive because, in a steady-state regime with no internal heat sources in the thermal insulation, the numerator and denominator have the same sign.

A parameter:

$$A = 0.335^4 \cdot B \cdot \left(2 \cdot \pi \cdot R_{lo} + ln(d)\right)^4, \tag{6}$$

where $B = Pr_{ext} \cdot (g \cdot h^3/\nu^2) \cdot (\lambda_{air}/\lambda_{ins})^4$ – parameter, which is also strictly positive;
$d = d/d_0$ – relative external insulation diameter;
$R_{\ell o} = R_{\ell o} \cdot \lambda_{ins}$ – thermal resistance of all layers beneath the thermal insulation, including internal heat transfer, if the cylinder is a pipe with a heat carrier.

Equations (3) and (4) can be treated as a function by d, thus

$$d\Delta T_{surf}/dd = -0.335^4 \cdot B \cdot (2 \cdot \pi \cdot R_{\ell o} + \ln d)^3/d \cdot \Delta T_{surf}^{5}/((\Delta T_{int} - \Delta T_{surf})^3 + 1.25 \cdot A \cdot \Delta T_{surf}^{4}) < 0 \tag{7}$$

$$R_{\ell} = R_{\ell o} + \left(\ln d/(2 \cdot \pi)\right) + (0.67 \cdot \pi)^{-1} \cdot \left(B \cdot \Delta T_{surf}\right)^{-0.25}, \tag{8}$$

$$\frac{dR_\ell}{dd} = \left(1 - \frac{d\cdot\left(\Delta T_{surf}\right)^{-1.25}\cdot d\Delta T_{surf}/dd}{2\cdot 0.67\cdot \tilde{B}^{0.25}}\right)/\left(2\cdot\pi\cdot d\right) > 0. \tag{9}$$

Derivative (7) is always negative, because all terms are positive, and $\Delta T_{int} > \Delta T_{surf}$ as the heat or “cold” source is in contact with the inner surface of the thermal insulation. Derivative (9) is always positive because all factors are positive except for $d\Delta T_{surf}/dd$, which is negative; consequently, the negation sign makes the expression in brackets positive.

Results and discussion

The positivity of the derivatives indicates a monotonic increase of the function (8). Therefore, for any parameter values, there is no critical radius of the vertical cylinder insulation. The calculations for expressions (7)-(9) have been implemented using Scilab for $d = 1 \div 1000\,\mathrm{m}$, $T_{ext} = 293.15\,\mathrm{K}$, $T_{int} = 313.15\,\mathrm{K}$, $R_{\ell o} \to 0$, $g = 9.81\,\mathrm{m\cdot s^{-2}}$, $\nu = 15.06\cdot 10^{-6}$, $\mathrm{m^2\cdot s^{-1}}$, $\lambda_{air} = 0.024\,\mathrm{W\cdot m^{-1}\cdot K^{-1}}$.

Graphical dependencies of the defined parameters (Fig. 1) confirm the absence of a critical radius. The following analysis is meaningless and the goal of this study is achieved. The insulation can be expanded until the outer surface achieves a sufficiently small overtemperature to facilitate laminar flow. Furthermore, it is feasible to continue expanding it for improved energy efficiency and enhanced accuracy in laboratory tests. It is advisable to use an expedient radius rather than a critical one, as the subsequent increase in the energy efficiency is not substantial. This allows rising the energy efficiency in different technical branches [45-50].

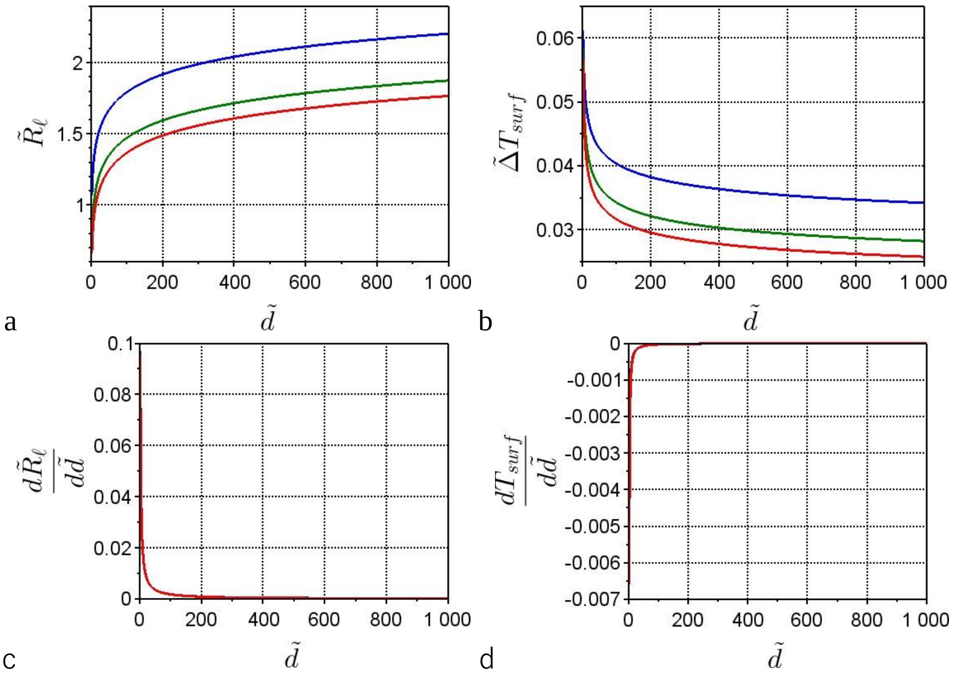

Fig. 1. **Results for B = 1 (blue); B = 5 (green); B = 10 (red):** a – total dimensionless heat transfer resistance coefficient; b – temperature on the outer surface of the thermal insulation; c – derivative of thermal resistance; d – derivative of the outer surface temperature

Validation

Let us focus on the practical and experimental evidence of the theoretical results, including validation. Cylindrical buildings have a radius, which is several orders of magnitude greater than the critical one for any building material. Nevertheless, as shown by more than half of century of building practice, the insulation of such buildings is effective. This is the first practical proof of the theoretical results. The authors created an experimental unit for thermocouple calibration (Fig. 2). It consists of a thermal flask with a copper tube inside of it with a neck on the cap. The flask is filled with water with the necessary calibration temperature. Because of the high specific heat of water, the temperature should not deviate more than ± 0.1 K from its average value during half an hour. But really this unit can keep the temperature inside the interval ± 0.1 K for 10 minutes. The decision of thermal insulation was made.

The external radius of Pinofol thermal insulation is 0.15 m with a thermal conductivity of 0.037 $W \cdot m^{-1} \cdot K^{-1}$ [51]. Using the heat transfer coefficient of the thermal surface as 8.7 $W \cdot m^{-2} \cdot K^{-1}$ [52], the critical radius is $\boldsymbol{d_{cr}} = \boldsymbol{\lambda / \alpha} =$ 0.004 m [53]. Even if we accept $\alpha = 0.5$ $W \cdot m^{-2} \cdot K^{-1}$ the critical radius will be 0.074 m, but we have 0.15 m. During half an hour, the temperature falls only for 0.15 K. Thus, we can use the average temperature as a calibration temperature value ± 0.075 K. The result shows the effectiveness of thermal insulation disregarding the radius greater than critical. Thus, the absence of a critical radius of vertical insulation is experimentally approved. As a result, the necessary heat capacity of the vertical thermal installation was achieved.

Fig. 2. **Experimental unit for thermocouple calibration with expedient insulation radius**

The findings can enhance the effectiveness of rural machinery. The same result can be achieved for any device with insulated piping. For example, a new calibration device for thermocouples and a gas exchange camera for CO_2 exchange in plants are created.

Conclusions

1. The critical radius theory has been debunked. It is grounded on a fake assumption that the heat transfer coefficient is not dependent on the radius.
2. It is essential to utilize an expedient diameter rather than a critical one, as the subsequent increase in the energy efficiency is not substantial.
3. Overcoming the critical diameter opens up the possibility of enhancing the effectiveness of devices, especially in rural machinery and technologies.

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Author contributions

Conceptualization, D. V. and V. M; methodology, D. V. and V. M.; software, D. V. and V. M.; validation, D. V., V. M., O. L. and T. T.; formal analysis, D. V. and V. M.; investigation, D. V. and V. M.; writing – original draft preparation, D. V.; writing-review and editing, D. V., V. M., O. L. and T. T.; project administration, D. V., T. T. and V. M.; funding acquisition, T. T. and O. L. All authors have read and agreed to the published version of the manuscript.

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