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Research paper

Heat transfer enhancement of a circular tube heat exchanger fitted with an elliptic shaped turbulator designed in the context of developing countries

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HIGHLIGHTS

- In developing countries, manufacture dispersions impact heat exchanger efficiency.
- Effects of turbulator design variables on heat transfer and pressure drop are studied.
- Nusselt number is predicted as a function of turbulator design variables.
- Fanning friction factor is also predicted through the same design variables.
- Surface-based dispersion was found to have the most impact on exchanger performance.

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ABSTRACT

Energy availability, heat conversion and transfer still represent an impediment to the food processing sector in developing countries. Optimisation of tubular heat exchangers remains a concern for equipment designers and manufacturers. This work assesses the performances of a turbulator in terms of heat transfer and fluid friction characteristics in a heat exchanger tube. The turbulator is designed based on an elliptic shape suited to be made locally. The geometric dispersions caused by this kind of manufacturing process were surveyed, and then considered in the study. Hence 26 turbulators, manufactured with or without geometric dispersions, and with 45° or 60° ellipses, were tested in three tubes of different diameters. To ensure the closest possible resemblance to actual applications, the tests were carried out using air as a working fluid, with a low range of Reynolds number (1700–8000 for heat transfer and 3000 to 16,000 for friction factor). The heat transfer rate in a tube fitted with a turbulator may be increased up to 900%, in turbulent flow and with a curve angle of 45°. On the flip side, there is a very big pressure drop. However, a surface-based dispersion of 30% which could be generated by local manufacturing leads to a 50% reduction in the friction factor, but only a 20% reduction in the Nusselt number. The models obtained will enable a multi-criteria analysis for heat exchanger optimisation in a context specific to developing countries.
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1. Introduction

The economies of many developing countries are largely reliant on agriculture. Faced with food insecurity and population growth [1], the development of the agricultural product processing sector is now recognized as a driving factor.

Food processing techniques generally combine several unit operations. One of them, drying, is the most common way of preserving and storing products. Many dryer models have been developed or optimised over the last twenty years [2] using various energy sources [3] including solar energy [4], in particular in developing countries. Yet drying is an operation classified as energy-intensive. Indeed, it calls on a large quantity of energy for the quantity of dried product and requires high power. Hence one of the major obstacles in terms of managing drying operations, in developing countries, remains energy access [5–7]. Among the energy alternatives, use of biomass as a fuel represents a reliable

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alternative [8]. For optimum conversion of this bioenergy, the interface between the biomass generator and the dryer proves to be an essential factor. To this end, a gas-air heat exchanger is most commonly used. In developing countries exchangers, most often tubular, are installed on drying units. They are easier to manufacture since the materials, although costly, are available in-situ and the local sheet metal working techniques are relatively well mastered. However, in the face of the low thermal efficiency generally found with these installations, and because of the cost of the materials and energies called for, these tubular exchangers need to be optimised.

The literature is teeming with concepts for high-performance heat exchangers which have been successfully developed in a Western production context [9]. In the particular case of tubular exchangers, they are optimised through increasing the heat transfer coefficient by means of passive or active methods, or a combination of the two [10].

Active methods require sophisticated external power sources such as electrostatic fields, fluid injection, and jet impingement [10], which explains why they are not widespread in developing countries.

In a review on passive techniques, Dewan et al. [11] specify their advantages, before surveying various heat transfer enhancement tools, in particular inserts or turbulators used in the flow passage. Thus, passive techniques are advantageous because inserts can be employed in an existing exchanger. As Durmus [12] or Guo [13] point out in their articles, these elements create a swirling flow and a thermal boundary layer disruption, favourable to thermal performance enhancement. Conversely, they lead to big pressure drops, which require use of additional pumping power. Various works investigate the decaying swirl flow type, where the swirling flow effect is generated by components (short twisted tapes, snails [12], axial vanes [14,15]) placed in the tube inlet. This type is considered useful and economic, since heat transfer increases without causing excessive pressure losses (respectively 50% and 100% according to Durmus et al. [12]). In the non-decaying flow type, the swirling flow effect is generated by components placed continuously or discontinuously in the tube. Promvonge and Eiamsa-ard [16] tested a combination of the two principles: conical turbulator in the tube with a snail entrance.

In the last few years, many works have been conducted to study the effect on heat transfer and on flow friction of various turbulator models with a non-decaying flow type. To date, inserts such circular-ring, helical or twisted tapes and wire coils have been widely studied. Durmus [17] studied the effect of angle of eight cut-out conical turbulators on the heat transfer rate and friction factor in a tube, while Promvonge studied it with the insertion of conical nozzle turbulators [18] or inclined horseshoe baffles [19] in a circular tube. In other works, the influence of various shapes, such as helical screw tape with or without a rod [20–23], circular-ring [24,25], twisted tapes [26–28], and a combination thereof [29] on the heat transfer and friction factor characteristics has been examined. Generally, the studies were processed experimentally, but sometimes also numerically [13,21]. Liu [30] reviews numerous works produced since 2004 on the various passive techniques listed above. He notes that the contribution of twisted tape inserts on heat transfer efficiency is better in laminar flow than in turbulent flow, unlike other techniques. In a review study, Hasanpour [31] points out that twisted tape inserts are the most widely used type for improving thermal transfer on exchangers. He presents their characteristics and associated performances for a number of models. To make the enhancement comparable between various enhancement devices, the thermal performance factor [32] is used.

In the context of developing countries, this type of device or turbulator is not used, because most of the geometries do not lend themselves to local manufacturing, and installing them in tubes may prove difficult. Generally, manufacturing methods such as bending machines, water jet or laser cutting techniques are not available. Conversely, the craftsmen are expert in the use of manual cutting, manual and bending, and possibly manufacturing jigs. These manufacturing methods are suited to the very low investment capacities of the craftsmen, as well as the low-revenue consumer market. However, it must be noted that the manufacture dispersions resulting from these manufacturing methods are high, which consequently affects the performance of the heat exchanger. The turbulator models available in the literature do not refer to this type of dispersion, since Western manufacturing conditions are much more refined.

Hence, the development of an optimised turbulator, whose geometry lends itself to local manufacture in developing countries, which implies countries with low available revenue among the economic players, represents an original work and one crucial for improving the performance of drying processes. An ellipse-based turbulator geometry, which can be cut and bent under artisanal conditions, was adopted for our study. To validate this choice, turbulator prototypes were made in two workshops in developing countries (Cameroon), to verify the feasibility of this geometry. It was possible to make the turbulators from sheet metal available on the local market, using the following tools: hammer, chisel, hand shears, metal saw, and portable grinder. In this way, the manufacture dispersions inherent in the manufacturing processes were detected. These dispersions were subsequently reproduced in Europe, in the manufacture of the turbulators for our study, in order to be able to characterise their impact on the performance of a heat exchanger.

The objective of this publication is to experimentally assess, and then model, the technical performance of this type of turbulator, in order to consequently size and optimise the heat exchangers. To ensure sufficiently generic models, we designed an experimental device able to vary the tube diameter, the bend angle of the turbulators and to apply the geometric dispersions.

2. Materials and methods

Based on an elliptic geometry, a turbulator model was outlined as per the definition drawing in Fig. 1a and b. The turbulator's elliptic strip was cut from sheet steel using the water jet technique (Northern context), or by manual shearing and grinding in Southern workshops, and then bent. On the turbulator made in developing countries, some major geometric dispersions were observed: several mm for all the dimensions of the cut ellipses, and up to 15° for the bend angle. They were reproduced on the turbulator model by geometric dispersions, both diametral (Δd; Fig. 1c) and angular (Δa; Fig. 1d).

It can be observed that the dimensions of the ellipses (l_{el} and L_{el}) are related to the internal diameter of the exchanger tube d_{int}, to the nominal bend angle α and the nominal diametral gap j_d via Eqs. (1) and (2):

$$l_{el} = d_{int} - j_d \tag{1}$$

$$L_{el} = \frac{l_{el}}{\cos \alpha} \tag{2}$$

The turbulator's performance was assessed by characterising the heat transfer and the pressure drop induced by its insertion into an exchanger tube. An original experimental device as shown in Fig. 2 was set up. This system incorporated an elementary unit of the exchanger, i.e. a single tube, subject to well-controlled thermal and

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