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OPTIMIZATION OF THE ARRAYS OF IMPINGING AIR JETS

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ABSTRACT

Use of impinging air jets to enhance heat and mass transfer rates is relatively new development in heating, cooling and drying operations in industry.

In this paper, an original optimization of nozzle arrays under impinging air jets was given for both academic and industrial users.

ÖZET

Çarpan hava jetleri ısı ve kütle transferi miktarlarını arttırdıklarından endüstride özellikle ısıtma, soğutma ve kurutma işlemlerinde kullanılması oldukça yeni bir gelişmedir.

Bu makalede, akademik ve endüstriyel kullanıcılar için çarpan hava jetlerinin orjinal optimizasyonu verildi.

1. INTRODUCTION

The applications of impingement cooling or heating are wide ranging, and include processes such as drying of paper and textiles, tempering of glass, cooling of electronic components and turbine blades. In an industrial application,

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such as calender cooling or cooling of high energy density electronic components, where highly localized cooling is desired, a single jet (or a row of widely-spaced jets) is usually used. However, when a larger surface is to be heated or cooled, as in the case of an impingement dryer for newsprint, tissue or textiles, rows or arrays of jets are preferred. Slot and circular jets are the two most frequently-encountered configurations. Figure 1 shows some of the nozzle geometries and arrangements used in practice[1].

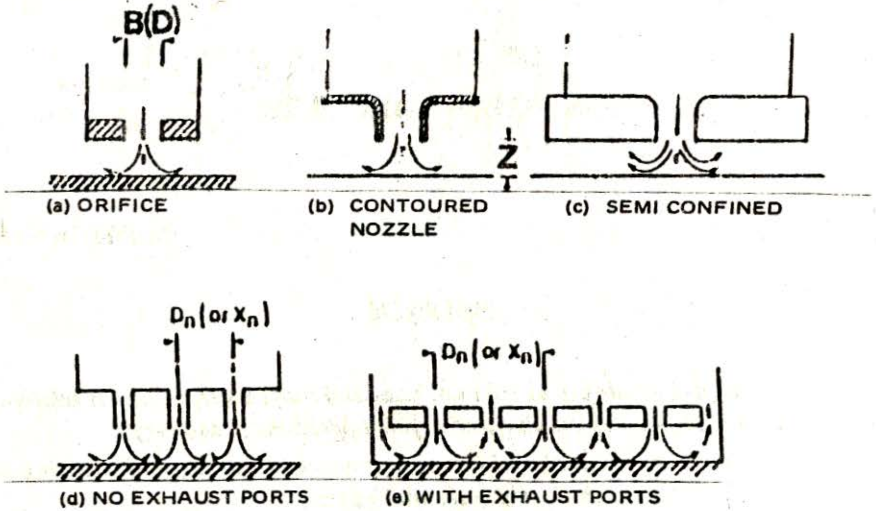

Figure: 1 - Flow geometries and arrangements

Considerable literature on impingement heat and mass transfer has been accumulated over nearly three decades. Nevertheless, the designer is still faced with the difficult task of selecting a jet configuration and optimising it for a given practical situation.

The objective of this paper is to provide data for industrial dryer design.

2. BRIEF DESCRIPTION OF MULTI-NOZZLE RIG

A multi-nozzle test rig has been constructed to provide data on arrays of nozzles. Detail description of rig was given in ref. 2. The horizontal impingement surface consists of an aluminium plate which is heated from below by hot water flowing in a number of narrow channels. A large constant head tank maintains steady-flow conditions. Average heat transfer coefficients, $\bar{h}$, may be calculated from the measured temperature drop of the water as it passes through the channels. Because of its size, this rig can be used to simulate actual industrial drying conditions.

3. AN INTRODUCTION TO OPTIMIZATION

Almost any problem in the design, operation and analysis of manufacturing plants and industrial processes can be reduced in the final analysis to the problem of determining either the largest or the smallest value of a function of several variables. Since optimization is the collective process of finding the set of conditions required to achieve the best result from a given situation, it follows that the techniques of optimization should be brought to bear on every task of practical importance.

In most aspects of industry continual improvement is an important feature. Thus the designer desires the largest production from given raw materials, the greatest profit from a fixed investment, and so on; optimization is a formal presentation of these ideas.

Improvement can be regarded from two view-points. Economic improvement provides an overall framework in which a given design should be examined since all problems should be considered within a financial structure. Some aspects, however, may not be directly related to company finances, and for this reason improvements are carried out on a technical basis while bearing in mind the economic criteria.

Any problem investigated in an optimization analysis should have as its objective the improvement of the system or systems. It should be obvious that, in order to improve any system, it is essential that at least one solution be obtainable for that system. In other words, by defining the inputs to a system, the resulting output can be found. If this is not possible, the system can not be designed or operated or controlled, far less optimized.

4. APPLICATION OF OPTIMIZATION TO THE ARRAYS OF IMPINGING JETS

The optimum combination of design parameters is that which gives the lowest costs. This might be based upon:-

1. Nozzle box capital costs - fabrication of nozzles, plenum (settling) chamber, materials, maintenance etc.

2. Nozzle box running costs - pumping power, fuel etc.

3. Total system capital costs - air systems (fan), cooling or heating section, energy for drying etc.

4. Total system costs - capital, interest, running operation etc.

The above economic factors are in broad terms, because actual conditions such as location, size of operation, type of material etc. will affect total costs and to some degree, cost ratios.

To increase the heat transfer coefficients usually requires a correspon-ding increase in fan power, although it can be seen from the results of this research[2] that the increases are not proportional. On the other hand, similar heat transfer coefficients can sometimes be achieved with fan of lower power rating and, hence, lower capital and running costs. Such considerations lead to the designer to carry out optimization studies.

In practice, each nozzle shape or configuration has advantages and disadvantages. For example, this research showed that slightly better heat transfer performance was achieved under the hole arrays, which would prove cheaper to manufacture in practice. However, the choice of such an arrangement will obviously place constraints on the design of an industrial plant. The importance of such a constraint will depend largely upon the size of firm and the funds it is wishing to allocate. To balance these aspects, a slot nozzle array will be and more compact than one using holes or round nozzles for the same heat transfer. In addition, two-dimensional (slot) jets are apparently preferred, in industrial uses for uniformity of heat transfer across the surface.

Selection of nozzle configuration should be based on cost of fabrication ease of maintenance and the selection of a suitable fan. The remarks which follow are drawn from the author's research largely on slot nozzles.

The designer should consider the following points:

a- Nozzle height, Z/B

At the nozzle outlet the turbulance level in the jet is relatively low. Due to intense mixing with the surrounding air the turbulence level rises and reaches a maximumm at approximately 8 effective slot widths from the nozzle outlet. This requires a knowledge of the discharge coefficient. For this reason, experiments show that the stagnation point heat transfer coefficients h_0 exhibits a maximum when the impingement surface is positioned at Z/B' = 8. Similarly, the average heat transfer coefficient $\bar{h}$ which is required for practical purposes obtained maximum providing Z/B' = 8 for any shape of nozzle configurations. Hardisty and Can[3] proved that the heat transfer coefficients exhibited a maximum at a dimensionless nozzle - plate spacing Z/B' = 8, independent of shape. They also found that for the nozzles used in this research the effective width B'(D') was related the actual nozzle size B(D) by the formula B'(D') = B(D)xC_D where C_D is coefficient of discharge of differently shaped nozzles.

b- Nozzle shape

Data on the effect of nozzle shape on heat transfer is presented here to determine optimum nozzle systems. Experimental results show that nozzle shape itself does not effect the heat transfer rates. Although nozzle shape does not directly affect heat transfer, the cost of nozzle fabrication must be taken into account by the designer.

c- Air velocity, V_E

Electrical power is required by the fans which provide the pressure rise needed to attain the required intake velocity, to overcome the frictional and flow losses in the ducts and bends, and to accelerate the air through the nozzles.

Heat transfer coefficients are proportional to air jet velocity and within the practical limits of the test rig no maximum was found out. An increase in air velocity can require a large rise in fan power, and also can produce an unwelcome, and indeed unacceptable, rise in noise level, both from fans and jets.

d- Air temperature, T_A

This effect has been partly discussed in ref. (2) and it was shown to be very marginal in the analysis.

e- Nozzle pitch, X_n

Nozzle pitch (or center to center spacing of slot nozzles) is directly related to optimum free area A_f (= B/X_n x 100) which is required by the designer. These studies showed that the "free or open area", ratio of the total nozzle outlet area to the heat transfer surface area, was a fundamental parameter. By expressing the results in terms of free area it was found possible to optimise the ratio of heat transfer to blower power, see Figs. 2-3.

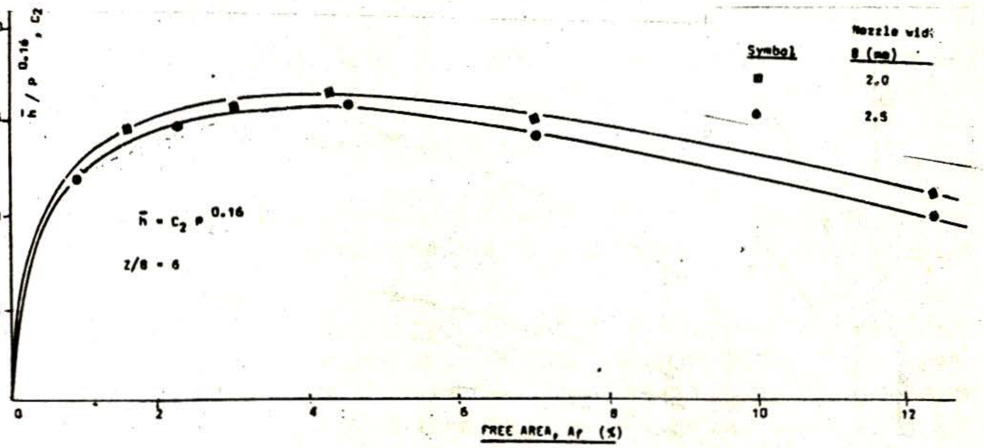

Figure: 2 - Variation of C2 with free area of arrays of slot nozzles

Figure 4 shows the mass flow/fan power characteristics for the different widths - same shape nozzles used in these experiments. By means of this graph the air flow characteristics of the different width nozzles may be compared. The graph could be used to select a nozzle system to suit a specified fan power. This is one example of this research could aid the designer. A more comprehensive discussion of this point will be given in refs. (4 and 5).

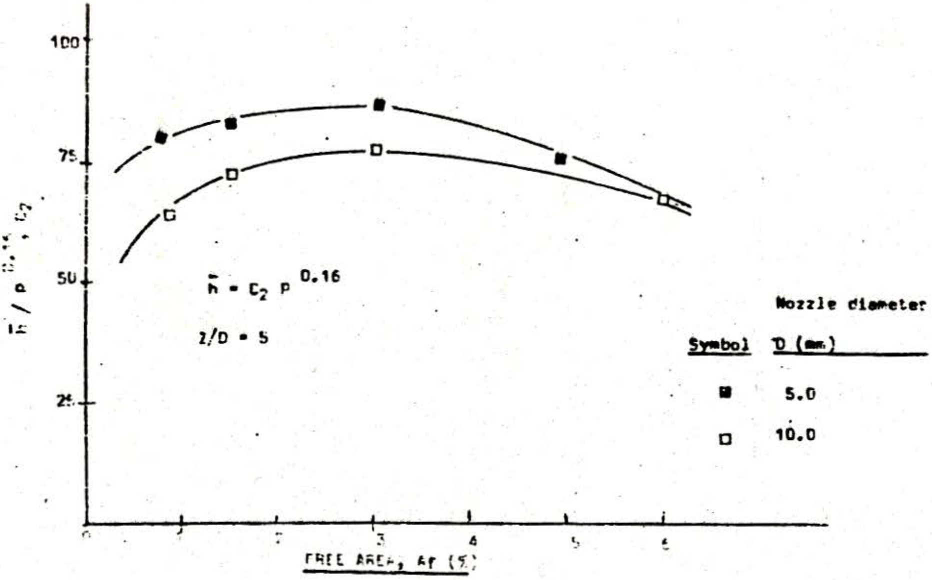

Figure: 3 - Variation of C2 with free area of arrays of circular holes

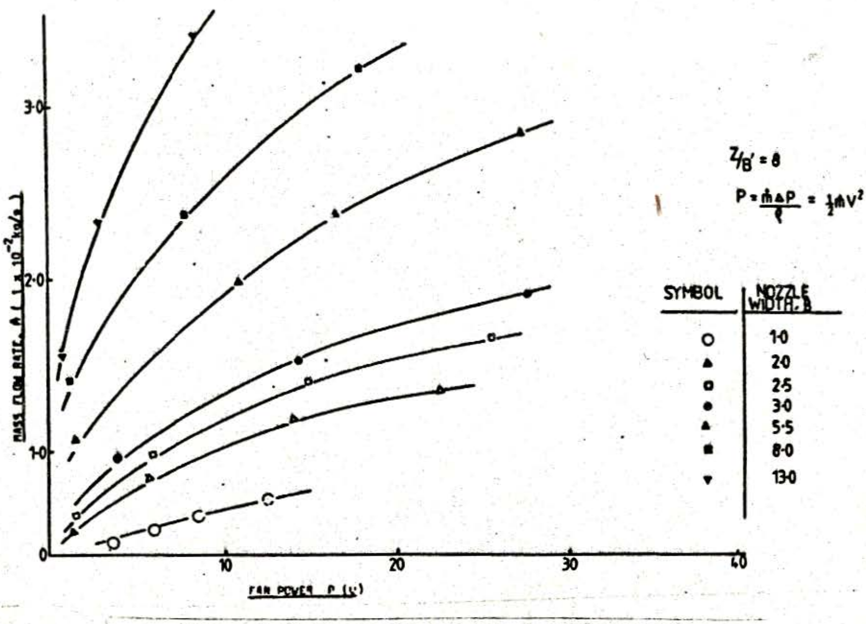

Figure: 4 - Fan power characteristics for different study *f- Secondary stagnation point (region)*

Despite of its importance, little research has been carried out into the secondary stagnation point which accurs midway between 2 slot jets, where 2 wall jet meets, interact and flow away from the surface. In particular it is difficult for designers to apply published heat transfer data for single nozzles to a multi-nozzle arrangement of complex geometry. This is because the designer lacks basic data on the effect of jet interaction and cross-flow. For example the effect on heat transfer of such a fundamental design variables such as optimum free area, nozzle pitch, nozzle size and nozzle height (Z/B' = 8) appears not to have been extensively investigated. In this study, because of its size, the multi-nozzle rig can be readily used to simulate actual industrial drying conditions. The original statement of design parameters can be written in the form:

$$\bar{h} = f\,(V_E,\ B(D),\ Z/B\ (Z/D),\ X_n\ (D_n)\,)$$

However, considering only heat transfer, selection of nozzle configuration is entirely dependent upon the following three different parameters:

1. Nozzle height, Z/B' = 8 (or Z/D' = 8) and $B' = B \times C_D$

   $D' = D \times C_D$

2. Nozzle width B (or diameter D)

   the narrowest slot width, B = 2.0 mm

   and the smallest hole diameter, D = 5.0 mm.

3. Nozzle pitch, X_n (or D_n) related to optimum free area A_f:

   A_f = 4.5 % for slots (B = 2.0 mm and B = 2.5 mm)

and

   A_f = 3.0 % for holes (D = 5.0 mm and D = 10.0 mm)

Both the experimental and theoretical investigations carried out in this research show that the 3 conditions are indeed the most relevant in the design of nozzle systems.

Based on the heat and mass transfer theory which is given in ref. (4), a computer program was written to calculate the dryer length to accomplish constant-rate drying. As a basis for this calculation, in for arrays of slot nozzles must be known. Typical results from this programme are summarised in Fig. 5.

5. CONCLUSION

An original optimization of nozzle arrays under impinging air jets was given for both academic and industrial users. Also optimum parameters presented here are simple and have wide applicability.

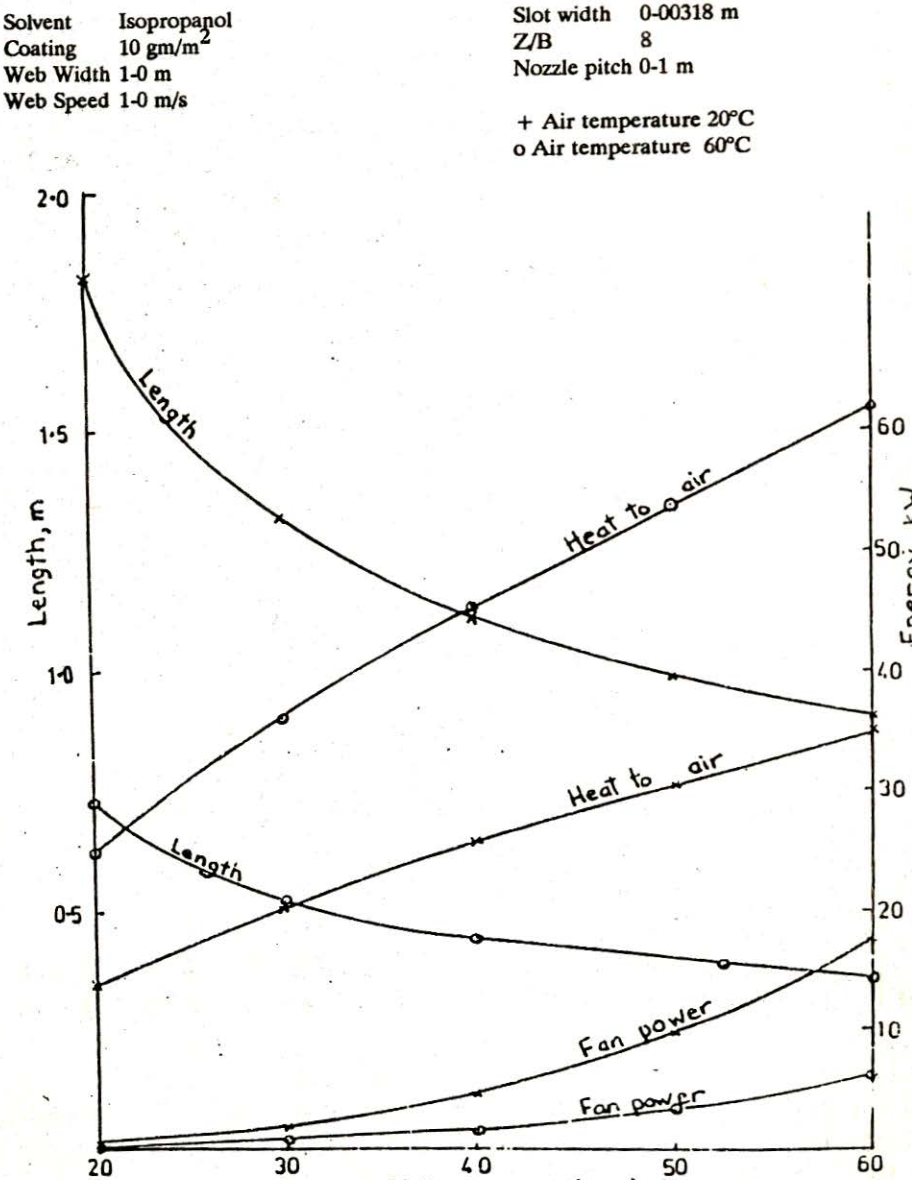

Figure: 5 - Consitant--rate dryer characteristics

Finally, it is considered that all aspects of this research are consistent one with another, thus demonstrating that the work is soundly based. It is also considered that the research described in this paper, provides particularly a rational basis for understanding of air jet dryers.

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