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Review

Increasing Heat and/or Mass Transfer Rates in Impinging Jets

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Abstract : First part of a survey drawing together findings of authors' research over a period of two decades on enhancing performance of impinging jets. The limiting factor is stagnant near-wall layer across which the transfer takes place by conduction. Results of research aimed at removing this limitation have been partly published but mostly in literature inaccessible to international readers. Flow visualizations played an important role in identifying the problem areas, leading to a number of novel implementation concepts to be described in the second part.

Keywords : Visualization, Heat and mass transfer, Impinging jets.

1. Introduction

The basic problem in convective heat and/or mass transport between fluid and a solid object is bringing the fluid as near to object wall as possible. Flows parallel to the object surface are not very efficient, being incapable to penetrate a layer of stagnant or near-stagnant fluid which forms at the wall, held there by viscosity. Impinging jets achieve exceptionally high transfer rates due to their perpendicular orientation towards the wall, as shown in the example of heating a plate by hot gas in Fig. 1. They are of importance for many areas of industry as listed in Tab. 1, because they can achieve the highest values of convective transport power density, Fig. 2. This is a product of heat transfer coefficient α_T [W / m^2 K] and the temperature difference ΔT [K] between the jet fluid and the wall. The extreme values shown in Fig. 2 are obtained mainly due to high ΔT. Nevertheless also the attainable α_T is highest in impinging jets compared with other cooling or heating methods. In extreme cases, levels as high as α_T = 50,000 W/m^{2}K, are achieved, though values of the order 1,000 W/m^{2}K are more common. They are usually expressed in non-dimensional form of the Nusselt number Nu, evaluated using the nozzle exit diameter as the reference length. The peak magnitudes under an impinging jet are from Nu = 150 (a rather low value for low-velocity jet from a nozzle placed quite far) to the achievable maxima of about Nu = 900. In the mass transfer problems, the dimensionless quantity analogous to Nu is the Sherwood number Sw, a non-dimensionalised density of diffusive mass flux.

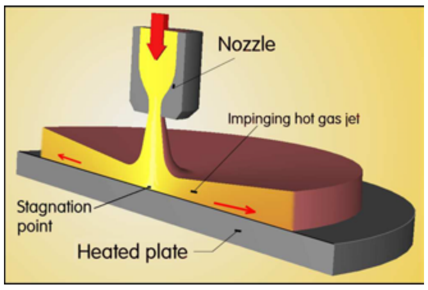
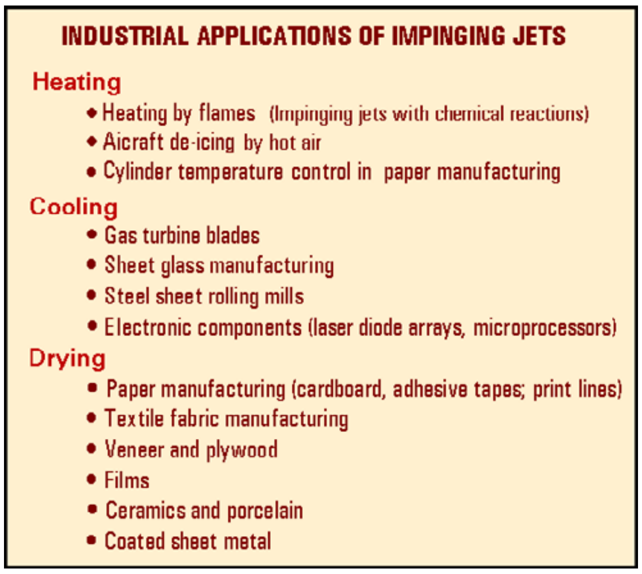


Fig. 1. (Above) An example of round impinging jet as used in industrial heating and drying processes. Planar jets issuing from slit nozzles are equally common.

Table 1. (Right) List of typical contemporary industrial uses of impinging jets.



INDUSTRIAL APPLICATIONS OF IMPINGING JETS

Heating
- Heating by flames (Impinging jets with chemical reactions)
- Aicraft de-icing by hot air
- Cylinder temperature control in paper manufacturing

Cooling
- Gas turbine blades
- Sheet glass manufacturing
- Steel sheet rolling mills
- Electronic components (laser diode arrays, microprocessors)

Drying
- Paper manufacturing (cardboard, adhesive tapes; print lines)
- Textile fabric manufacturing
- Veneer and plywood
- Films
- Ceramics and porcelain
- Coated sheet metal

2. Dominant Vortices

Literature on impinging jets research is quite extensive – not only because of the importance for industrial applications, Tab. 1 but also stimulated by the requirements of such fields as aeronautics (e.g. the effects on the ground of vertically taking off and landing airplanes) and civil engineering (e.g. air curtains in public buildings). Yet several intriguing basic problems still remain, experimental investigations revealing a number of not fully understood features. Numerical computations do not provide reliable guidance because impinging jets are prone to difficulties associated with turbulence modeling, e.g. due to the strong turbulence anisotropy. One of the unsettled problems are the secondary, off-axis maxima of transfer coefficients on the surface, found especially for small relative wall distances, smaller than three nozzle diameters. Gardon and Akfirat (1962) were probably the first among those who attempted to explain them as a consequence of laminar/turbulent transition. Small dependence on Reynolds number makes this explanation doubtful, however. According to a different hypothesis by one of the present authors (Tesař 1998e - based upon detailed anemometric investigations) the off-axis maxima should be the result of "lifting" the convected turbulence due to action of standing coherent vortices forming the curvature centres of the fluid pathline "bends". These vortices, observed in 1991 by Popiel and Trass, were later detected as coherent structures by Tesař and Střílka (1997- using a novel detection method). They are called "*dominant vortices*" by Tesař and Barker (2002) since they strongly influence and even dominate the flowfield. In most current applications the impinging jets are turbulent (turbulence is welcome to increase the convective transport intensity), with stochastic vortical motions in the flow, mainly generated in the shear layers on jet edges. The dominant vortices differ from them by being coherent (Tesař and Střílka, 1997), statistically stationary, and of larger size. They influence the conditions at the wall by generating induced rotational motions that direct away from the wall the fluid flow trajectories, downstream from the impingement. This effect of the

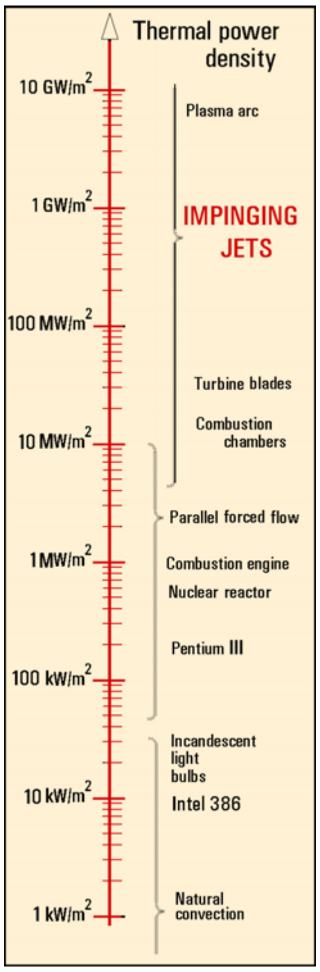


Fig. 2. Density of thermal power transfer in various engineering cooling tasks, spanning 6 orders of magnitude.

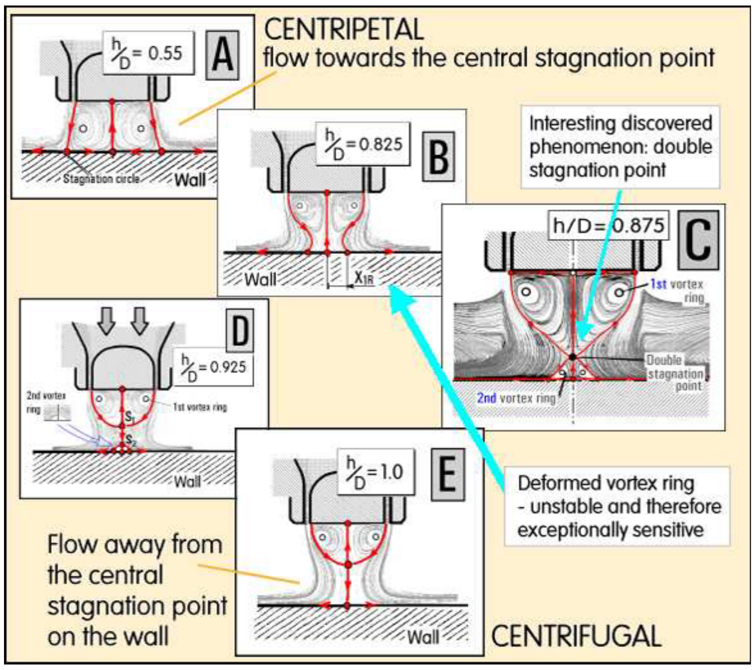


Fig. 3. Computed steady state flow pathlines in annular impinging jets. It is possible to distinguish five configurations, among which there is the case C with the interesting double stagnation point and also the unstable regime B with elongated annular vortex (Tesař et al. 2001a, 2001c).

vortices on the wall transfer phenomena was recently also ascertained by visualizations of Meola et al. (2000).

Other vortical structures of essential influence on the flowfield are present in impinging jets created by nozzles containing an insert blocking a part of the exit. This is the case of the "combined" planar nozzle of Trávníček and Křížek 1999, with an insert dividing the outflow into two slits. Such nozzles flows may exhibit bistability and other interesting phenomena. Figure 3 presents a survey of observed flowfield configurations in the corresponding axisymmetric case. The internal standing vortex ring can reach to the wall (case A in Fig. 3) at small wall distances *h/D* where it generates the "centripetal" flow towards the central stagnation point. At large wall distances *h/D* it reaches only to the intermediate stagnation point (case B in Fig. 3) and generates on the wall the "centrifugal" flow away from the axis.

3. Challenge of Small Scale Applications

All applications listed in Tab. 1 would benefit from higher transfer rate effectiveness. In some of them it is particularly urgent, of particular importance being the cooling of electronic components. The development history of microprocessors – such as the gradual decrease of the transistor structure size (measured in μm in Fig. 4) – is known to follow, with remarkable precision, the Moore's exponential law (Brenner 2001). This makes possible to predict quite reliably that already in the next microprocessor generation the required cooling power density is likely to become the main limiting factor to further progress. To evade it, more efficient cooling is studied by all principal microprocessor manufacturers. The high achievable thermal power density makes impinging jets an important candidate. The small size, however, leads to low Reynolds numbers, with turbulence ineffective or missing and the viscous layer thick. Another area in which microfluidic sized impinging jet cooling is becoming important are exothermal chemical microreactors. The density of generated thermal power in some perspective applications in microchemistry (fuel conversion and reforming) is so high that the basic idea of "numbering up" of microreactors is endangered by the limits posed by the necessary cooling system.

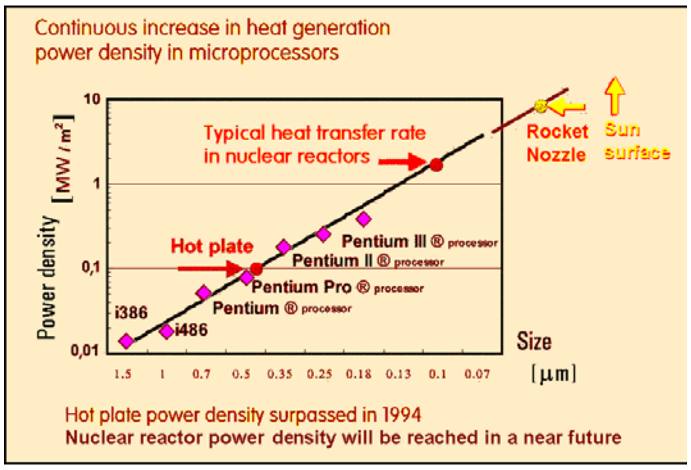


Fig. 4. Important contemporary cooling problem: heat removal from microprocessors. Already the present Pentium generation surpasses the conditions existing at heated stove plate. Within next two processor generations the values are likely to reach the conditions existing in the core of nuclear reactors (based on several sources, in particular G. Moore, and P. Gelsinger – as well as Brenner (2001)).

Yet another, not new but nevertheless still challenging field where cooling effectiveness is the limiting factor to further progress are turbine blades, where especially in the most thermally loaded small blades of first turbine stages the small dimensions and high gas viscosity due to high temperature leads also to very small Reynolds numbers, in fact in the same range as in microfluidics.

4. Limits Imposed by Stagnant (Sub-) Layer

Even under an impinging jet, there is a stagnant layer on the surface - related to the viscous sublayer of classical turbulent boundary layers - across which heat must pass by conduction, because it cannot be penetrated by fluid motions. Though often extremely thin, the layer is the limiting factor of the whole transport process. It could be photographed, Fig. 5, by the time-dependent dye admission technique (Tesař and Barker, 2002), but to make it discernible required exceptional, low Re conditions.

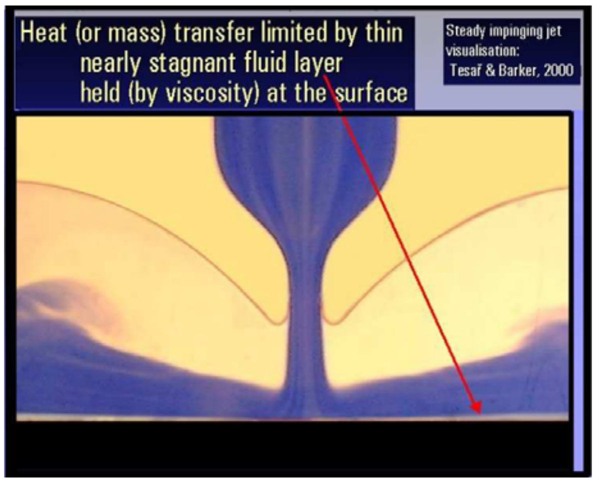


Fig. 5. Photograph of planar impinging jet in transmitted light. After sudden addition of dye into the supplied fluid, stagnant regions remain transparent – among them the thin wall layer that acts as a thermal insulator. This is a low Reynolds number (*Re* = 1,500) case where the layer is exceptionally thick.

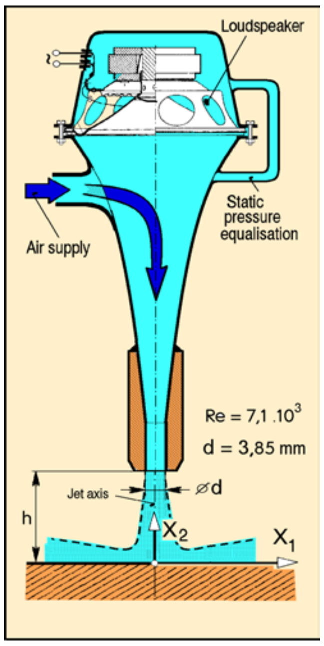


Fig. 6. An early experiment (Tesař 1998a) with varicose excitation of a round impinging jet.

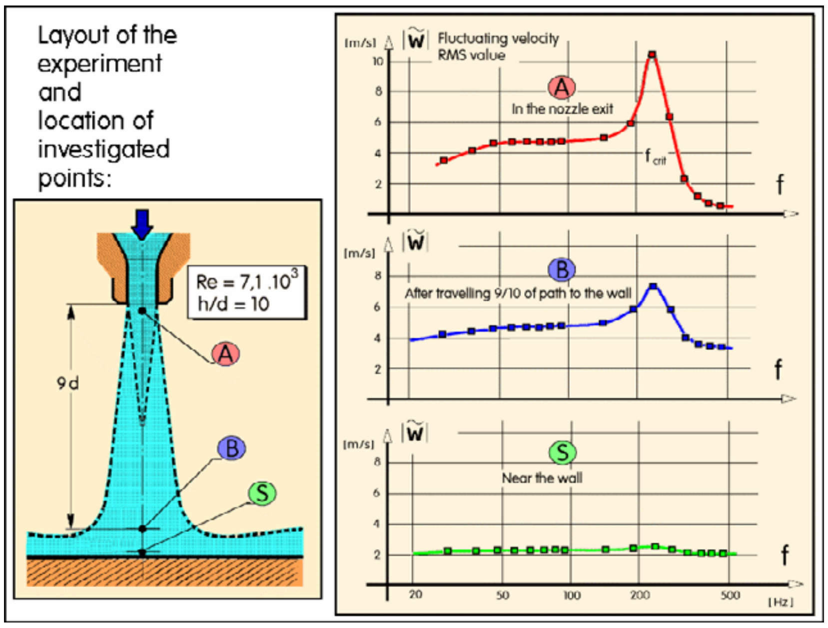


Fig. 7. Hot-wire anemometric measurements of damping the oscillation in an impinging jet (Fig. 6.) on its approach to the (Tesař 1998c). The plotted RMS magnitude of the oscillatory flow velocity component was measured in the nozzle exit A and two downstream locations B and S at different excitation frequencies *f*.

Despite being so thin, the layer accounts for nearly all the thermal resistance. Its thickness may be roughly estimated as equivalent conductive layer thickness δ_T exhibiting the same effective value the Nusselt number, typically $Nu = 500$. With $D = 1$ mm diameter nozzle (quite large size for microdevice cooling) in air, $\lambda = 25.10^{-3}$ W/Km, the layer may be roughly estimated as being only about 0.002 mm thin. This small layer thickness makes it not amenable to direct experimental investigation (hot wire diameters are larger than this thickness and at any rate hot wire anemometry is unsuitable because of radiation cooling effect of the near wall, while optical methods, like LDA or PIV, are limited by light diffraction on the fluid/solid interface).

5. Periodic Forcing

In an unsteady flow starting from rest, the near-stagnant (sub) layer thickness grows with square root of elapsed time. One possibility how to destroy its insulating effect is to remove it and let grow anew periodically. This may be achieved by superposing strong pulsation on the flow (e.g. Tesař, Jílek, and Randa 2002). The effect should be particularly pronounced at low *Re* (e.g. in the microdevices) as it can there substitute the weak or missing turbulent fluctuation. This idea is not new and has been already tried in other shear flow heat transfer problems. Tesař and Marvan 1989 may be cited as an example of positive experience with heat transfer improvement by pulsations produced by a no-moving-part fluidic oscillator. The improvement characteristically exhibited resonant peaks to which the driving frequency has to be attuned.

Early oppositions to the idea raised the objection of complexity of the additional machinery required for modulating the nozzle flow. A piston pulsator or mechanically driven valves are too high a price for the achieved improvement. Fortunately, the recent progress of fluidics - the technique of fluid flow control without moving mechanical devices, e.g. Tesař (1998b) - offers now a nearly perfect solution to this problem. The oscillation may be generated by simply built fluidic oscillators, requiring no external drive. Recently, other attractive means of flow pulsation generation by electroactive polymer organic materials became available. An example is the deformation caused by motion of ions in ion-exchange polymer-metal composites or the electrically driven volume changes in liquid crystal gels.

More profound problems poses adjustment of excitation parameters, such as the oscillation frequency. If the conditions are not properly adjusted, the off-resonant pulsation is totally useless (e.g. Sreekant et al., 2003). This is because the near-wall layer, responsible for most of the thermal resistance, exhibits a strong and selective damping capability (Tesař 1998a). This enables it to absorb improperly chosen oscillation without any enhancement effect. An instructive example of the absorbing capability of the jet is presented in Fig. 7 as the result of experimental investigations of an axisymmetric impinging jet with varicose (axial) excitation using the rig shown in Fig. 6. The disadvantage of this excitation method is the dependence of amplitude of generated pulsation on frequency, caused by acoustic resonance in the cavity upstream from the nozzle. In the case from Fig. 6 the main cavity resonance frequency f_{crit} was about 250 Hz. The measured RMS value of the unsteady velocity component, plotted in Fig. 7, contained coherent as well as stochastic turbulent components. The coherent components dominated below f_{crit}, while the turbulent components dominated at $f > f_{crit}$. A fact apparent in Fig. 7 is the damping effect influencing more strongly the large amplitude resonant motion. As the wall is approached the local maximum at f_{crit} practically disappears, while oscillation at other frequencies is not very much damped, especially between the locations A and B. Most damping at the non-resonant range takes place very near to the wall, below the point B. The amplitudes of the turbulent component ($f > f_{crit}$) between A and B actually increase, no doubt by conversion from coherent motions to stochastic ones. The coherent oscillation ($f < f_{crit}$) decreased between A and B almost negligibly, certainly much less than on the short remaining segment from B to S – despite the path between A and B representing 90 % of the total nozzle-to-wall distance h.

In this experiment it was not possible to position the hot wire probe into the really strongly damping near-wall conduction layer. Nevertheless the data for B and S show the strong damping as the wall is approached. The very small damping occurring on the distance from A to B is not very surprising. Most of this distance lies within the jet potential core, in which there is almost no viscous dissipation. This, however, makes the more surprising the disappearance of the large amplitude motions and conversion of their energy into the energy of turbulent vortices.

6. Unwelcome Vortical Structures

An explanation seems to follow from the visualization experiments (unpublished, made with J. Barker). A typical still photograph of the pulsed impinging jet is shown in Fig. 8. The next Fig. 9 presents example of frames from video recording. Obviously, the pulsation causes a formation of vortical structures in the jet mixing layers immediately below the nozzle exit, symmetrically on both sides of the jet core (in Fig. 8 and the upper two frames of Fig. 9). This is thought to be associated with the Tesař-Ho phenomenon – the local maximum of fluctuations observed earlier (in non-impinging jets) at this location (Tesař and Ho, 1998; Tesař 1998b). In the video record, the two vortices (or vortex ring in an axisymmetric case) are seen to move downwards, "descending on the jet" (actually carried along with the jet flow). They finally (as seen in the bottom frame in Fig. 9) disappear in the turbulent motion nearer to the wall, while a new pair (or new vortex ring in the axisymmetric case) is then formed at the nozzle exit. The energy of the input pulsation, instead of being used in accordance with the intentions to destroy the near-wall layer or at least for penetration through it, is spent on producing the transversal vortical motions in the mixing layers immediately below the nozzle exit. The apparent paradox of the dissipation in what should be essentially the "inviscid" potential core is explained by these processes taking place in the shear flow of the mixing layer. The conversion into turbulence takes place by decay of these large vortices.

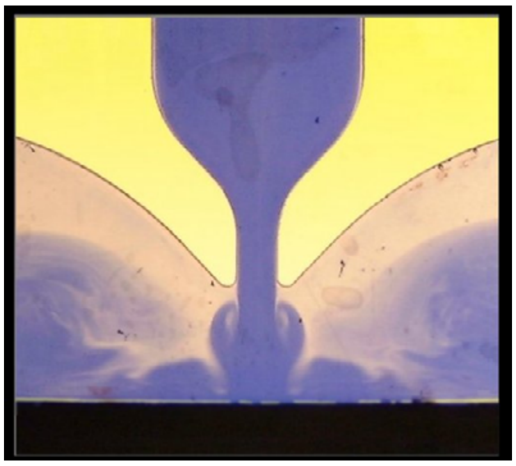


Fig. 8. (Above) Flow visualization photograph of pulsed impinging jet (made with student Mr. Barker) showing a vortex structure that forms downstream from the nozzle exit and travels along the jet.

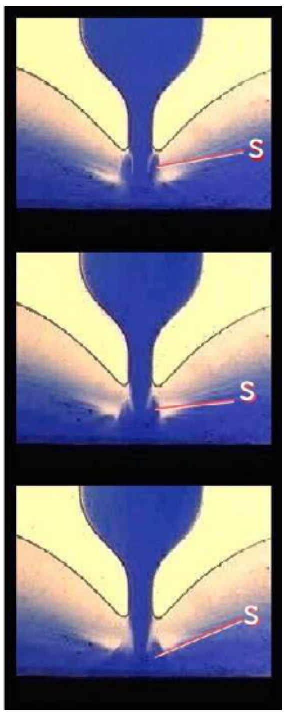


Fig. 9. (Left) Frames from the video record of visualized pulsed impinging jet showing the descent of the vortex structure s (though to be associated with the Tesař-Ho local fluctuation maximum (Tesař and Ho, 1998, Tesař 1998) down the sides of the jet before it approaches the stagnation region.

7. Conclusions

Improvement in cooling/heating and/or drying performance of impinging is possible by periodic unsteadiness, ranging from small disturbances up to the nozzle flow reversals in synthetic and hybrid jets. Not all attempts are successful: the wall layer can absorb and dissipate the pulsation energy. Also the shear layers surrounding the jet can absorb it and spend on formation of unwanted vortical structures. An answer may be in special nozzle configurations, of which the annular nozzle is an example. The next part of this survey will present a number of novel implementation concepts – pulsating annular and synthetic impinging jets – making practical use of these investigation results for increasing the heat and/or mass transfer rate.

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