Miniaturization and Process Intensification - smaller means better?

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Depletion of natural resources combined with the extending footprint of mankind has led to a shift in importance of research and development topics. Emphasis is now focused on resource efficiency as a primary objective. This is directly connected to intensification of processes in terms of resource consumption, yield, selectivity and economic output. The European Roadmap of Process Intensification [1] identifies several measures, amongst which miniaturization is named to be a very promising one.

It is a well-known fact that minimization of heat and mass transfer resistances lead to tremendous increase in the related transport capacities. Thus, miniaturized devices will play a key role in future industrial applications and transport systems as well as in the re-design of existing processes that directly impact on the daily life of citizens, ranging from industrial technologies to personal equipment.

However, there are significant gaps in the fundamental knowledge-base for both mass and heat transfer processes in the micro scale. Current research is primarily focused on phase transition or multi-phase flows, with less attention paid to single-phase gas flows. Liquid flows in microscale are considered to be understood and well described.

Measurement systems with sufficiently high temporal and spatial resolution to clarify phenomena in micro scale are in many cases not available, and modelling of such processes is exceptionally challenging. Because of this, pre-calculation and design of miniaturized devices is often based on trial-and-error. Thus, very often it is not possible to predict whether a process really can gain advantages from miniaturized equipment or suffer by the disadvantages. In terms of industrial processes, this leads to the situation that application of miniaturized equipment is a risk very often not taken.

Almost all parts of technology are influenced by miniaturization concerns. At the moment, the highest visible impact is to see on information technology and electronics. Nowhere else is the need to miniaturize, compact and intensify processes as high as here, dealing with huge volumes and high flows of information. Other technological topics are naturally not so much influenced, e.g. architecture. However, even here impacts are to see, since the development of miniaturized LED light has opened new opportunities for architectural design. Another example for the use of miniaturized systems is not so prominent but the most common one: the exhaust gas catalyst system for combustion engines is based on mini- or microscale channels serving as catalytically active ducts for the combustion exhaust gases.

It has to be carefully decided for which application miniaturization is a real advantage, just transforms into a new technology without major advantages or disadvantages, or may be even reducing efficiency of processes. The publication presented here will focus on applications of miniaturized devices in process engineering. Thus, considerations on heat transfer and mass transfer as well as some other technological aspects linked to these will be the primary content.

The basic principle behind intensification of thermal and chemical processes is the enhancement of transport processes by minimization of transport distances as well as reduction of transport resistances. Therefore, it is not necessary to have always microstructures inside devices, it is also suitable to miniaturize and structure the fluid streams, bring them close together and take advantage from this. Heat transfer as well as mass transport are strongly promoted by the small distances, thus, heat transfer time as well as mixing time can reach millisecond or even microsecond range. Besides, in most cases miniaturization in process engineering is linked to modularization, which allows combine different functionalities more easily than with conventionally sized equipment. This leads to a unique situation: While combination of different tasks in macro scale equipment runs on the time scale (residence time in each device has to be kept according to the limitations of the device vessel to reach reasonable effects), the modular micro scale equipment can be combined on a local scale by separating single parts of the process to optimized miniaturized devices and combining them to form the complete process. The enhancement in heat and mass transfer is high, thus, optimum conditions can be reached much more easily than with conventional sized devices [2], [3]. However, there are some major issues to be taken into account, which in many cases prevent the application of microscale devices to processes. Amongst those is the unknown long-term behavior, but also problems with fouling, cleaning and overall efficiency, taking heat transfer, mass transfer and pressure losses into account.

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