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ON THE DEVELOPMENT OF AN ENERGY EFFICIENT PACKING FOR VACUUM DISTILLATION

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Abstract
This paper describes an approach to develop a novel structured packing for vacuum distillation, with superior characteristics compared to the conventional packings. The contribution of elementary pressure drop mechanisms to the heat and mass transfer is investigated using the complementary modelling at different levels of detailisation. The main objective of this study is to identify the "useful" and to eliminate the "useless" pressure drop mechanisms, thus reducing the energy input while keeping the same packing heat and mass transfer efficiency.

Keywords: distillation, packing, turbulent structure, CFD, hydrodynamic analogy

1. Introduction

It is well known that in distillation applications, the efficiency of conventional structured packings with similar specific geometric surface area is a function of pressure drop. Therefore, an increase in separation efficiency cannot be gained without a corresponding increase in pressure drop. However, a comparison of the ratio pressure drop to separation efficiency for different conventional structured packings demonstrates substantial deviations. This implies existence of "useful" and "useless" pressure drop mechanisms with respect to heat and mass transfer[1,2].

The majority of structured packings used in distillation towers are designed to operate in the turbulent regime with the aim to achieve high rates of heat and mass transfer. The turbulent structures lead to dissipation of the vapour flow kinetic energy at different scales and locations which can be classified as elementary pressure drop mechanisms. However, the turbulent structures do not all contribute to the transport rates equally.

An excellent review on the ways to identify and characterise the flow structure in contact devices is given by Joshi et al.[3,4]. The authors claim that a significant decrease (5 to 10 times) of the total kinetic energy input (pressure drop) at the same separation efficiency can be achieved, when the turbulent energy dissipation occurs at desired locations. Hence, to be able to optimise the flow patterns, it is important to understand the relation between the flow structure and the transport phenomena.

The objective of this work is to study the contribution of different turbulent structures to the heat and mass transfer in a structured packing under vacuum distillation conditions. In these applications, the maximal operating temperature in a tower is limited either by the product quality requirements (standard colour number) or its thermal degradation. In common practice, the tower is designed to operate at very low loadings in order to minimise the total pressure drop. This leads to a substantial overdesign of the tower diameter and operations far below the actual hydraulic limits of the installed packing. If the same separation efficiency could be achieved at lower pressure drop, smaller tower diameters would be acceptable, thus leading to a substantial decrease of investment costs.

2. Approach

It is known that the main resistance to the heat and mass transfer in distillation is mainly located in the vapour phase and the liquid-phase mass transfer resistance can be neglected. It is expected, that the transport rates in these applications can be influenced solely by adjusting the intensity of the gas-phase turbulence distribution by the packing geometry modifications.

In this study, a geometrically simple wire gauze packing composed of vertically oriented mesh layers with deep drawn spacers is used (see Figure 1). Such a packing geometry was taken considering the simplicity of modification (e.g. spacer geometry, spatial arrangement of the spacers in adjacent layers). Wire gauze was preferred due to its advantageous wetting behaviour under rather low liquid loadings that are common for vacuum distillation. As a weave type, the so-called five-heddle-twill-weave (see Figure 2 a) was chosen owning to its better liquid distribution properties compared to the other standard weave types.

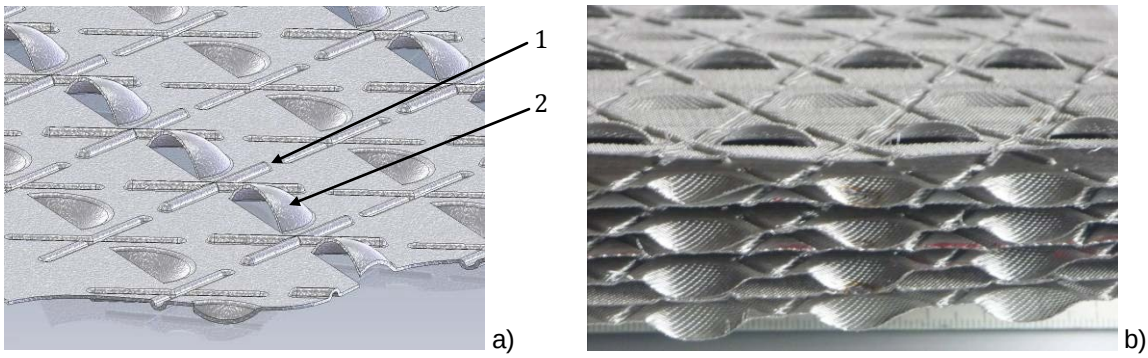

Figure 1. a) Single layer of the packing demonstrating the basic macro-geometry (patent pending): 1 – embossed formations to improve the packing performance, 2 – deep drawn spacers; b) Photograph of the packing

The influence of the packing geometry on the separation efficiency was investigated as follows:

1) As the first step, the elementary dissipation mechanisms in the gas-phase flow in the packing are studied by the computational fluid dynamics (CFD) methods. The simulations of the single-phase gas flow are carried out at micro- and macro-scale, the former revealing the influence of the surface structure offered by the wire gauze and the latter elucidating the effect of the spacer geometry. Dry pressure drop, local distribution of turbulent eddy viscosity and its integral mean value are estimated from the simulation results.

2) As the second step, the packing separation efficiency is estimated using the hydrodynamic analogy (HA) approach[5]. According to this approach, the real complex two-phase flows in a packing is replaced by a similar combination of geometrically simpler flow patterns. The description of the heat and mass transfer in these flow patterns is carried out rigorously and requires no empirical correlations. The integral mean eddy viscosity and the averaged eddy viscosity distribution, determined in the first step, are used as input parameters for the HA-model in order to take the gas-phase-turbulence at different locations into account.

For every modification of the packing geometry, the pressure drop and the corresponding separation efficiency are estimated by the methods described above. This procedure is repeated until a packing geometry is found which has minimal pressure drop at maximal possible separation efficiency.

3. CFD modelling and simulation

The objective of the CFD-simulations is to obtain the pressure drop and the local eddy viscosity distribution, the latter being an input parameter for the HA model. Due to the large-scale difference between the packing surface structure, spacer geometry and the whole arrangement, the CFD-simulations of the gas flow are carried out separately at micro-scale and at macro-scale. This results into substantial reduction of the computational complexity.

For all simulations, a grid independency analysis and a model validation against experimental data are performed. Experiments are carried out in a wind tunnel in order to determine the dry pressure drop caused by the wire gauze packing geometry. A comparison of the measured and calculated pressure drop demonstrated their good agreement. With the validated model, detailed studies are preformed to investigate the impact of the packing geometry on the gas-phase flow.

3.1 Numerical simulation of the gas flow at micro-scale

Figure 2 shows the structure of the five-heddle-twill-weave wire gauze studied in this work and the periodic element used in the CFD-simulations. From these simulations, detailed information about the velocity profile and turbulence intensity or turbulent viscosity in the near-wall region can be obtained. The hydraulic characteristics of the gas flow in this region are in the focus of numerous investigations, since the major resistance to heat and mass transfer is concentrated in this area, within a few micrometers from the interface.

The micro-scale simulation results can be used to adjust the near-wall energy dissipation rate, turbulent kinetic energy and velocity profile in the direction normal to the wall using modified wall functions. This special "rough-wall" modification can be applied in the macro-scale simulation, where the wire gauze is not resolved directly by the numerical mesh, but treated as a geometrically smooth wall with modified turbulence wall functions.

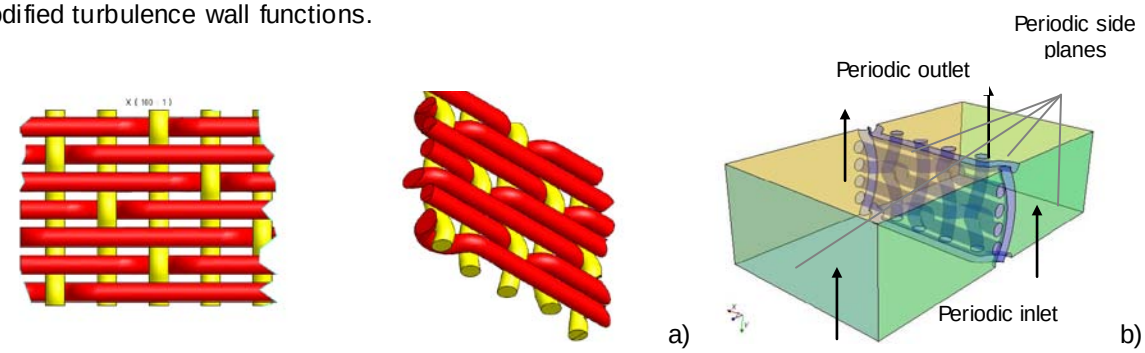

Figure 2. a) Structure of five-heddle-twill-weave wire gauze, b) periodic element used in the simulations

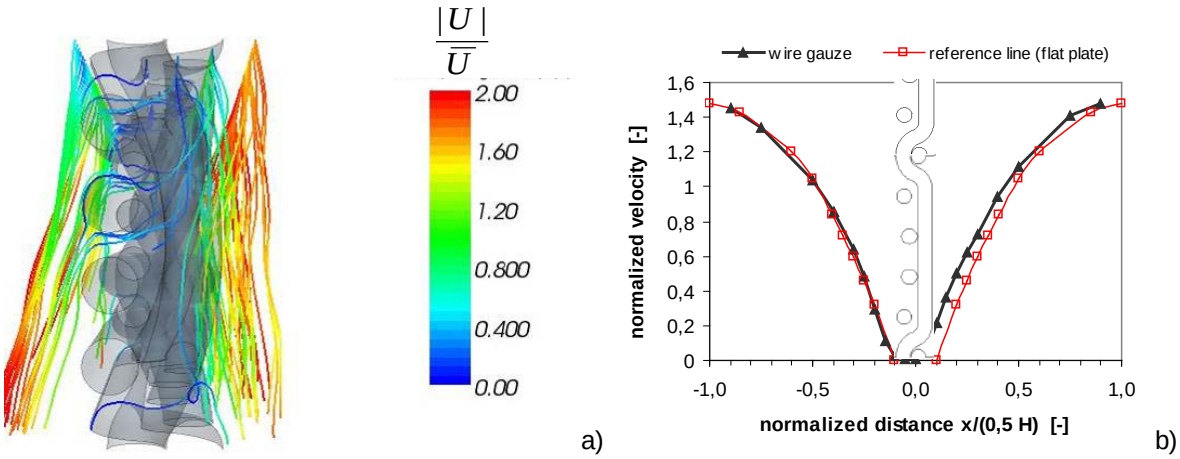

Figure 3. a) Streamlines around the wire; colour scale for velocity magnitude, normalised with its mean value; b) Calculated averaged velocity profile, H-distance between the layers

3.2 Numerical simulation of the gas flow at macro-scale

The second step of the CFD-modelling and simulation is the investigation of the elementary dissipation mechanisms in the gas-phase flow at macro scale. The calculations aim at determining the influence of the spacer geometry and spatial arrangement of the spacers in the adjacent layers. Due to the limitation of computational power, the packing geometry is reduced to a periodic element composed of two wire gauze layers. Figure 4 a) illustrates the 3 D computational model of the periodic element. Because of the complex geometry, an unstructured tetrahedral grid was used (Figure 4 b)). To reach grid independent results, about one million tetrahedral and prismatic mesh elements were necessary.

For the description of the gas-phase flow inside the computational domain, the momentum and continuity equations are used. The flow within the periodic element is considered incompressible and steady-state. The simulations are preformed for laminar and turbulent flow regime and for different gas volumetric flow rates corresponding to F-factors between 0.5 and 3.8. To simulate the fully developed flow neglecting inlet and wall effects, periodic boundary conditions are imposed at the inlet and outlet

of the domain with respect to the main flow direction. At all other surfaces, the standard no-slip boundary condition is imposed.

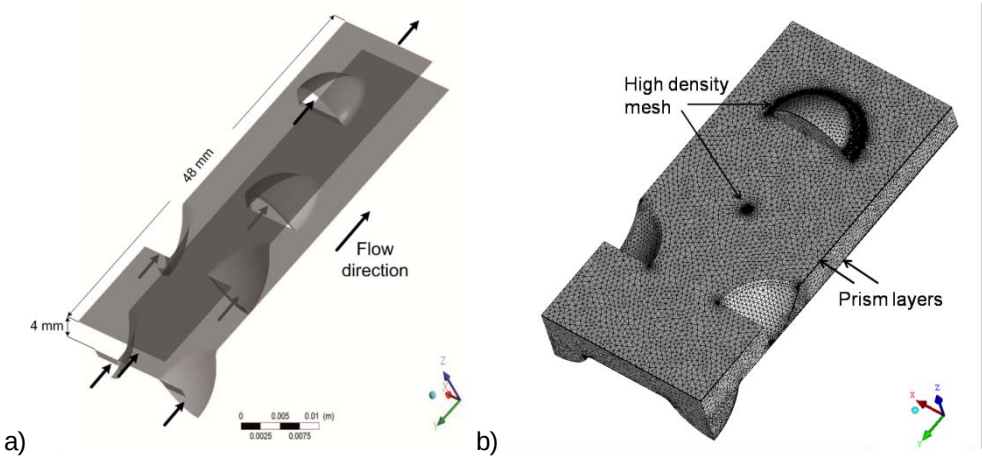

Figure 4. a) Periodic element of the packing, b) Computational domain

Figure 5 shows the streamlines inside the periodic element for the gas loading factor equal to 2.2. While high velocities in areas adjacent to the half-spherical spacers can be observed, marginal velocity and flow separation behind the spacers is visible. These areas reveal possible mixing points and dead zones. With regard to the HA approach, these results provide an estimate of the length of undisturbed flow. Further conclusions can be drawn from the local distribution of turbulent eddy viscosity. The latter is represented as a function of the relevant co-ordinate and applied within the HA-model, subject to the respective packing geometry, in order to take the gas-phase turbulence into account.

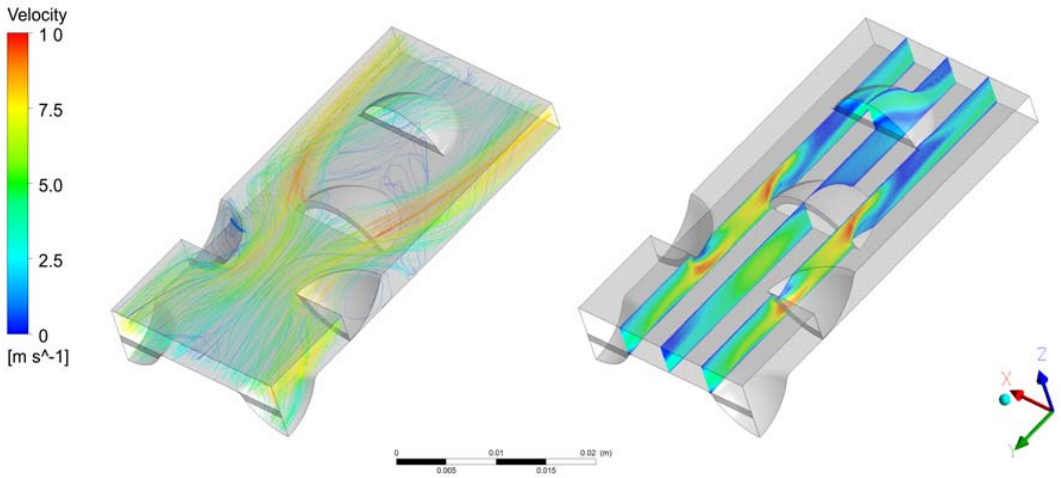

Figure 5. Streamlines inside the periodic element

4. Modelling with the hydrodynamic analogy approach

The HA approach is an alternative way to describe the hydrodynamics and transport phenomena in processes in which the exact location of the phase boundaries is not possible, yet the fluid pattern possess some regularity or structure which can be mirrored by an analogy with more simple flow elements. The basic idea of the approach is a reasonable replacement of the actual complex hydrodynamics in a column by a combination of geometrically simpler flow patterns. Such a geometric simplification has to be done in agreement with experimental observations of fluid flow, which plays a crucial part for the successful application of this approach. Once the observed complex flow is reproduced by a sequence of the simplified flow patterns, the partial differential equations of momentum, energy and mass transfer can be applied to govern the transport phenomena in an entire separation column.

First applications of the HA approach were suggested for the liquid-film pertraction and zero-gravity distillation processes[5]. Successful examples were given for distillation processes in columns equipped with corrugated sheet structured packings[6,7].

4.1 Physical model development

The geometric characteristics and experimental observations of the packing shown above provide valuable information which helps to capture the gas and liquid flow patterns. The main structure of the packing is given by vertically oriented mesh layers.

The gas flow takes place between the two layers. Because of the half-spherical openings of the deep drawn spacers, a part of the gas is redirected into the next layer. Accordingly, at certain distances, there is a renewal of the gas flow. The renewal can be approximated by an ideal mixing of the gas phase. Therefore, the distance between two mixing points in the gas phase, z_G, is equivalent to the packing height, when the whole gas flow between two layers is renewed due to the redirection. On the other hand, CFD simulations can show where mixing points appear in the gas phase.

The distribution of the liquid phase on the wire gauze layers is dominated by capillary forces. Thus, a total wetting of the packing can be assumed. The deep drawn spacers and the x-stampings cause a redirection and mixing of the liquid flow.

Based on the assumptions made for the fluid flow and on the geometric characteristics of the packing, a physical model can be developed (see Figure 7). Taking the packing structure into account, vertical plain sheets represent the basis of the physical model. The gas flow between the sheets depends on the operating conditions and varies from laminar to turbulent flow. Redirection by the semi-spherical openings is accounted for by periodical ideal mixing of the gas in the HA model.

The liquid flows counter currently to the gas phase in form of laminar non-wavy films over the mesh layers. Additionally, a uniform distribution of both phases in radial direction is assumed, i.e. no maldistribution is taken into account in the model. The periodical ideal mixing approximation is necessary to account for real mixing caused by the abrupt change in the flow direction. For the liquid phase, the length of the undisturbed flow z_L is determined in accordance with the redirection caused by the spacers and the x-stampings.

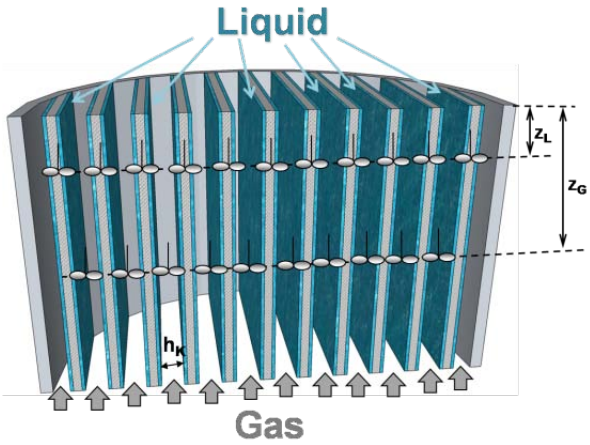

Figure 7. Hydrodynamic-analogy-based physical model of the investigated structured packing

The mathematical model describing this arrangement comprises partial differential equations written for the gas and liquid phases and coupled through the boundary conditions at the phase interface. Numerical solution of this system yields the local temperature and composition fields, which can be used to determine the integral characteristics, e.g., the packing separation efficiency.

4.2 Influence of the gas-phase turbulence

The HA-model takes the gas-phase turbulence into account by considering the local turbulent eddy viscosity. The influence of the eddy viscosity distribution on the separation efficiency is shown in Fig-

ure 8. The radial distribution (curves 1-3 in Figure 8 a) is varied while the integral mean value and, hence, the resulting pressure drop remain equal for each function. Figure 8 b demonstrates calculated concentration profiles of a light boiling component for the corresponding eddy viscosity profiles. Obviously, under the same pressure drop, different separation efficiency depending on eddy viscosity distribution can be achieved. This can be well captured by the proposed model.

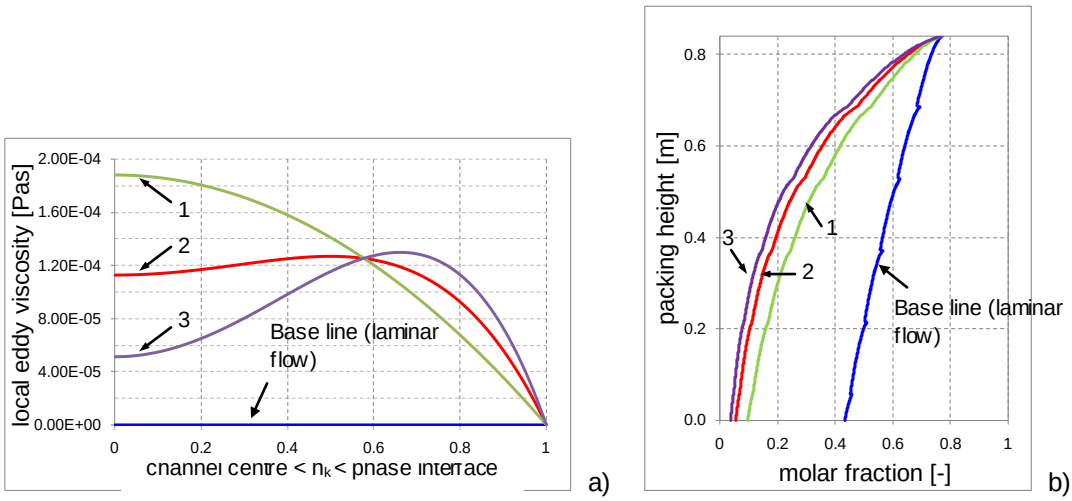

Figure 8. Influence of the eddy viscosity distribution on the concentration profiles in a packing bed: a) radial eddy viscosity distribution, b) calculated concentration profiles of a light boiling component

5. Conclusions

In this article, a systematic approach is presented which helps to develop column internals with improved characteristics. Above all the reduction of "useless" pressure drop can be advantageous. The approach is illustrated with the new packing implemented for a vacuum distillation process. It comprises CFD simulation of the single-phase gas-phase flow at two different scales (micro and macro) in order to capture the elementary energy dissipation mechanisms and to determine the local turbulent eddy viscosity distribution. The latter is then used in the following step, in which the hydrodynamic analogy modelling is applied providing the information on the transport phenomena in an entire distillation column. The presented approach allows the influence of the dissipation mechanisms on the packing separation efficiency to be evaluated.

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