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Review Report

From Cystic Duct to Static Mixer: A Serendipitous Journey via Flow Visualization

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This paper reports how an investigation into the role of bile flow in the human cystic duct in a study of bile duct disease, led through flow visualization to the design of a novel static mixer.

1. Introduction

The cystic duct is the conduit through which bile flows into and out of the gallbladder. The *valves of Heister* in the lumen of the human cystic duct consist of several semi-lunar or crescent-shaped folds which complicate the geometry as shown in Fig. 1 (Bird et al., 2006). Initially the experimental study focused on examining the role of the cystic duct a variable restrictor and used a simple, idealized model of the duct comprising a tube with a series of semi-circular segmental baffles, Fig. 2, which represented the *valves of Heister* (Ooi et al., 2004: Al-Atabi et al., 2004, 2005a). Clinical data has suggested that the flow is laminar with a maximum Reynolds number of about 40.

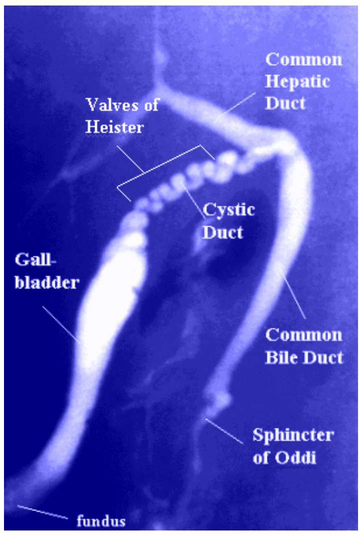

Fig. 1. Human biliary system.

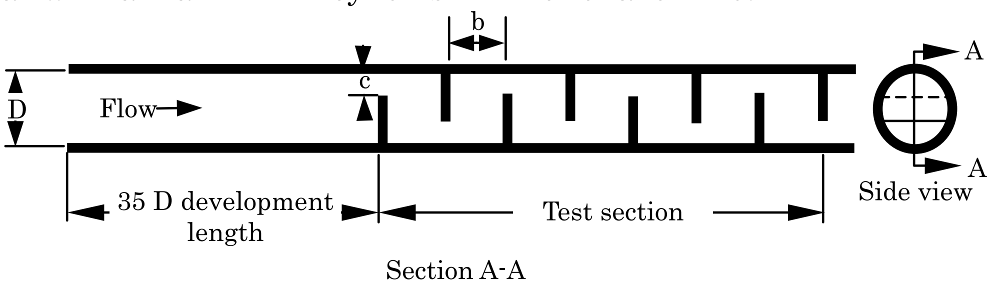

Fig. 2. Schematic of the idealized cystic duct/static mixer.

Fig. 3. Examples of industrial static mixers.

The idealised cystic duct model comprises a 21.5 mm diameter tube with equi-spaced alternating semi-circular baffles, Fig. 2. Water from a constant head tank flows through a 40D development length before entering the model through a bell-mouthed entry. The water discharges via a 20D long outlet pipe, Fig. 4. Three models with baffle clearance, c/D = 0.7, 0.5 and 0.3, were used.

The flow was visualized by a fluorescent dye (Fluorescene) injected under gravity upstream of the development length. A burette stores and controls the dye flow rate to the hypothermic needle the outlet of which is located at the geometric centre of the pipe. A fluorescent lamp provided illumination. Pressure drop was measured with an inclined manometer with pressure tappings located 1.5D upstream of the first baffle and 1.5D downstream of the last baffle. The flow rate was obtained by weighing the water over a fixed time period. The Reynolds number, Re, is based on the tube diameter and flow rate.

The flow visualization carried out for the bile flow in the idealised cystic duct model showed that the equi-spaced baffles in Fig. 2 trigger the initially laminar streamline to change rapidly into a condition where the flow structure appears non-laminar. This visualization suggests that the baffles have enhanced the rate of mixing in the otherwise laminar flow condition. This led the study into a totally new direction; the design of a novel static mixer. Static mixers, such as those in Fig. 3 have no moving parts and use flow energy alone to mix fluids for either continuous or batch production.

2. The Idealised Cystic Duct as a Static Mixer

Static mixer performance is assessed by the degree of mixing between water and brine (25 % NaCl w/w). Water was supplied continuously to the static mixer by the constant head tank. Brine was injected via a 3 mm diameter tube in the geometric centre of the tube 3D upstream of the first baffle. A multi-point sampling probe (Fig. 5) extracted nine mixture samples simultaneously from nine points evenly distributed across the pipe cross section 3D downstream of the mixer. The cross sectional area of the probe is < 0.5 % of the cross sectional area of the mixer. The refraction index of the sample was measured using a refractometer (calibrated with known concentrations of brine (Al-Atabi et al 2006) to infer the average brine concentration in the sample.

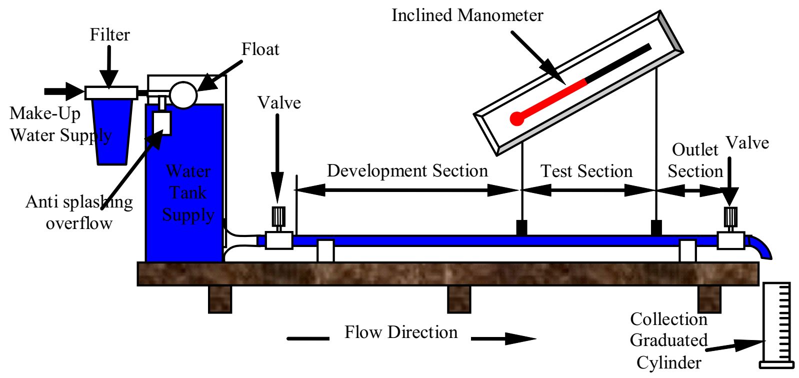

Fig. 4. Experimental set-up.

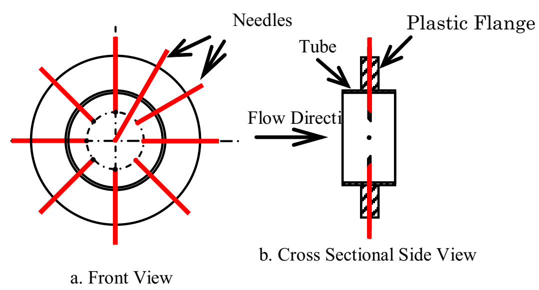

Fig. 5. The multi-point sampling probe.

3. Results and Discussion

Initially, the effect of the idealised bile duct was examined from the point of view of the cystic duct and how its shape affected the flow pattern through it. Photographs of the side view of the flow going from left to right with a variety of clearances are shown in Figs. 6-8 (Al-Atabi et al., 2004). At a Reynolds number below 100, the flow appears laminar throughout with clearly separated streamlines from the first to the last baffles. At the largest clearance ratio, c/D = 0.7 (Fig. 6) the flow negotiates the baffles easily and the streamlines are wavy with only a small recirculation behind the baffles. At c/D = 0.5 (Fig. 7), the baffles require the flow to assume a more curvilinear path and the recirculation increases significantly. At the smallest clearance, c/D = 0.3 (Fig. 8 (Al-Atabi et al., 2005b)) the recirculation zone occupies most of the volume between successive baffles. This implies that at higher Reynolds numbers, the baffles rapidly trigger the initially laminar streamline flow into a condition, where the flow structure appears non-laminar. The point at which this occurs depends on both c/D and Re; at c/D = 0.7 the organized structure typical of a laminar flow is no longer evident after the fifth baffle at Re ≈ 360, but with the smallest clearance of c/D = 0.3, this occurred after the third baffle at Re ≈150. From the top (Fig. 9) it will be seen that for c/D = 0.3 and Re = 150, the recirculation behind the first two baffles appear as two symmetrical counter-rotating vortices, and that after the third baffle, the flow is no longer laminar as the streamlines are indiscernible.

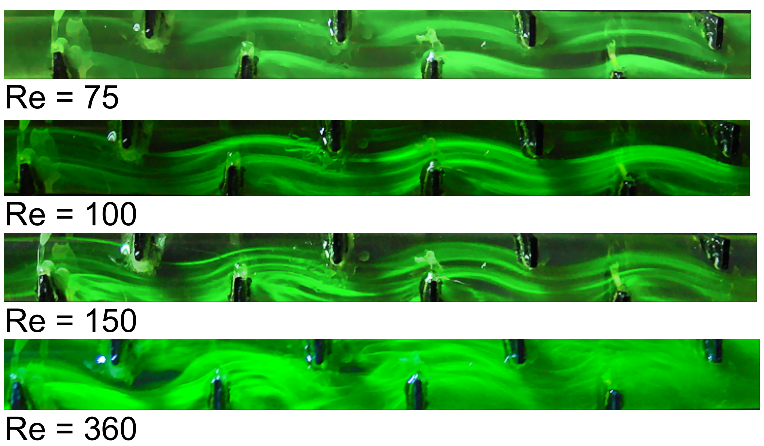

Fig. 6. Flow structure c/D = 0.7.

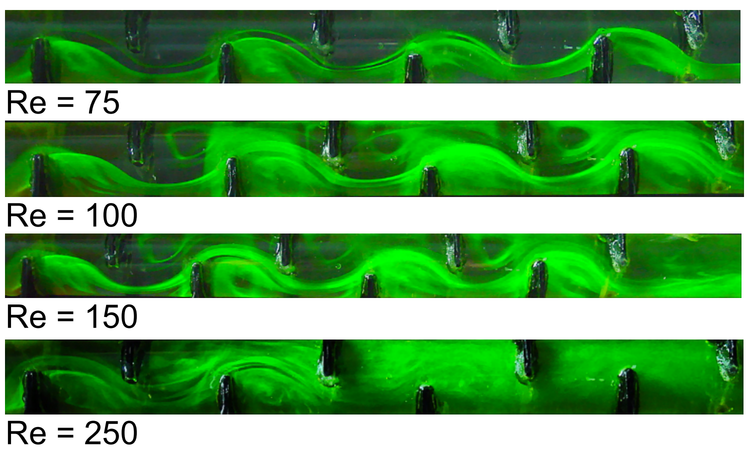

Fig. 7. Flow structure c/D = 0.5.

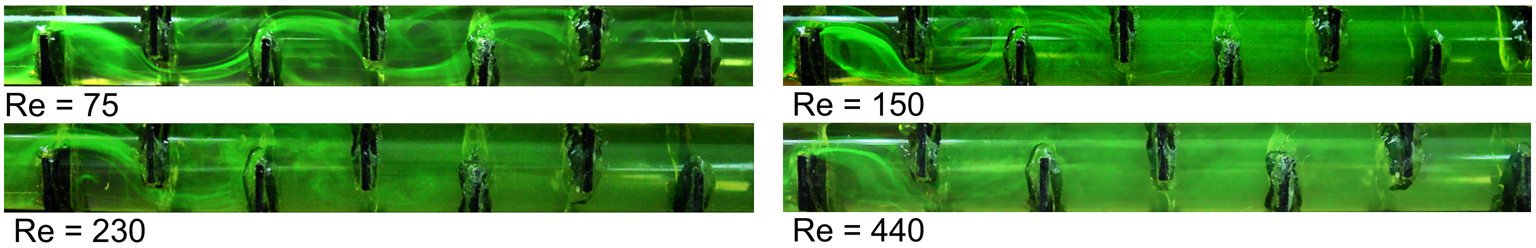

Fig. 8. Flow structure c/D = 0.3.

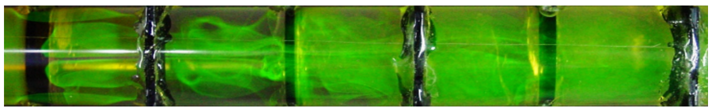

Fig. 9. Flow structure c/D = 0.3 top view. Re = 150.

Figure 10 shows that decreasing c/D increases the friction factor over that of the equivalent Poiseuille flow condition. The baffles are expected to increase flow resistance but flow visualization in Figs. 6-9 suggests that the change in the flow condition from laminar to non-laminar may also be a contributing factor. For the cystic duct, these results suggest that the more complicated the structure is (more Valves of Hesiter or a longer duct) the harder the gallbladder has to contract to create the pressure gradient to expel bile through the cystic duct (Ooi et al., 2004). Inability of the gallbladder to expel bile efficiently may lead to prolonged statis of bile, a factor leading to the formation of gallstones The flow visualization results also suggest that the non-laminar flow condition may result in an increase in mixing when compared with a laminar flow at the same nominal Reynolds number.

Once it was noticed that the idealised cystic duct actually constituted a novel and potentially excellent static mixer, it was decided to examine its performance in this new rôle.

The performance of a mixer usually is characterised by the coefficient of variance, CoV $= \sigma/\overline{x}$, where σ is the standard deviation and $\overline{x}$ the mean concentration. Zero CoV indicates perfect mixing; conversely a value of unity means no mixing. In a typical industrial mixing process, an additive is considered well mixed at 5 % CoV (Etchells et al., 2004).

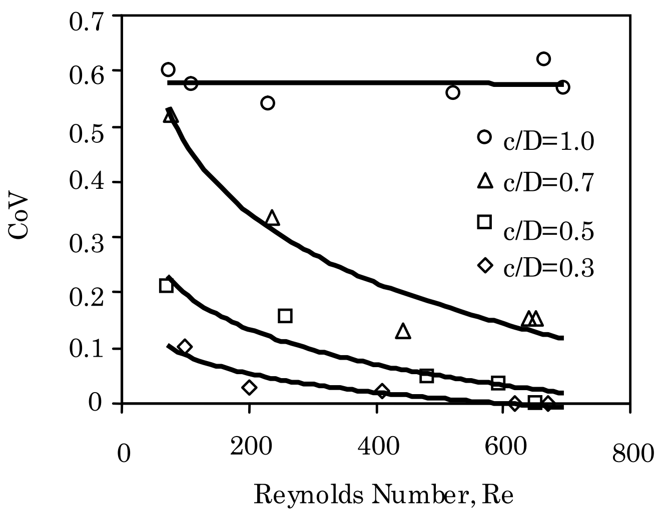

Fig. 10. CoV vs Re.

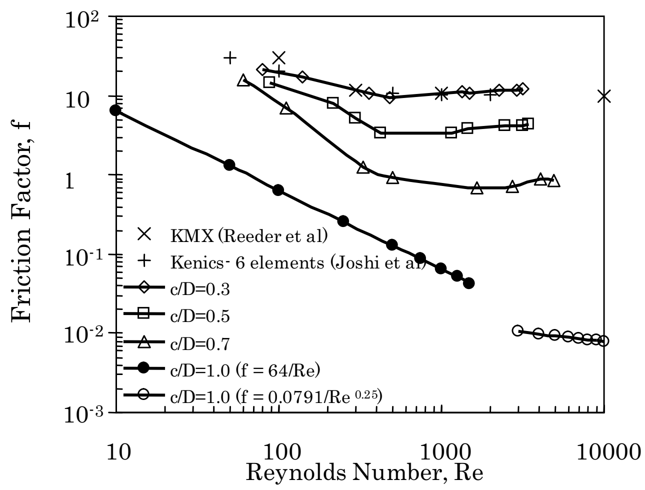

Fig. 11. Friction Factor vs Re.

The idealised cystic duct models were employed as the proposed mixers. Figure 10 shows the CoV for the three mixers and a smooth pipe for Reynolds numbers between 50 and 700. For the latter (c/D = 1.0) the CoV is largely independent of Re as the flow is laminar and there is little mixing between streamlines; molecular diffusion being an inefficient mixing process. The CoVs for the mixers are significantly smaller than those for Poiseuille flow in all cases; the smaller the c/D, the smaller the CoV. The CoVs also decrease sharply with increasing Re for the three mixers and hence, the c/D = 0.3 mixer shows the smallest CoV. The degree of mixing ranges from six times smaller than t an equivalent laminar flow at Re = 50 to over an order of magnitude smaller at Re = 600. The flow visualization in Figs. 6-9 clearly indicates that the enhanced mixing in these mixers is due to the baffles triggering the initially laminar flow to transition and non-laminar flow condition.

Figure 11 shows the friction factor for the mixers, Poiseuille flow, turbulent flow in circular tube and two commercial static mixers (KMX (Reeder, 2001) and Kenics mixers (Joshi, 1995)) for 50 < Re < 5000. As expected, the friction factors of the all the mixers are higher than those for flow in circular tubes at the same Re. The friction factors for the proposed mixers with c/D = 0.5 and 0.7 are much lower than those of the two commercial mixers, whereas that for c/D = 0.3 is similar. This suggests that the same degree of mixing could be obtained from this family of mixers as current commercial ones but with lower flow losses, which would make them more economic to run.

4. Conclusions

An investigation into the role of fluid mechanics in gallbladder diseases employed flow visualization to study the effects of cystic duct geometry on bile flow. The results indicated that the more complex the geometry of the cystic duct is, the greater the pressure gradient required to produce a given bile flow rate from the gallbladder, which may lead to prolonged bile stasis in the gallbladder and/or inefficient emptying of the gallbladder.

The flow visualization also showed that an idealised cystic duct geometry, with equi-spaced alternating baffles in a circular tube may trigger an initially laminar flow into a non-laminar condition. This suggested to the authors that such a device may be utilised as a static mixer. Measurements of the coefficient of variance in the mixing of brine with water in the proposed mixer showed a high degree of mixing for an initially laminar flow. Measured pressure losses are at least as low as those of published mixers. Further work is continuing on optimising the geometry, baffle spacing per unit length and clearance ratio to significantly enhance the rate of mixing in the flow.

This novel mixing device, a practical and economical alternative to the static mixers currently in use, was initially conceived from the data extracted from the flow visualisation of the cystic duct. This shows that in science and engineering analysis, tools such as flow visualisation, used to explain the physical processes that surround us can - with a leap of the imagination - lead us to the type of inventions that we would not otherwise be able to conceive.

References

Al-Atabi, M., Chin, S. and Luo, X., Flow Structures in Circular Tubes with Segmental Baffles, Journal of Flow Visualization and Image Processing, 12 (2005a), 301-311.

Al-Atabi, M., Chin, S. and Luo, X., Visualization of the Flow in Circular Tube with Segmental Baffles at Low Reynolds Numbers, Proceedings of the 11th International Symposium on Flow Visualization (11ISFV) (Notre Dame, USA.), (2004).

Al-Atabi, M. T., Chin, S. B. and Luo, X. Y., Visualisation of mixing of flow in circular tubes with segmental baffles, Journal of Visualization, 8-2 (2005b), 89.

Al-Atabi, M. T., Chin, S. B., Luo, X. Y. and Beck, S. B. M., Analysis of The Staggered-Baffle Static Mixer, Proceedings of the 12th European Conference on Mixing Bologna, (2006), 647-654.

Bird, N. C., Ooi, R. C., Luo, X. Y., Chin, S. B. and Johnson, A. G., Investigation of the Functional Three-Dimensional Anatomy of the Human Cystic Duct: A single Helix?, Clinical Anatomy, 19 (2006), 528-534.

Etchells III, A. W. and Meyer, C. F., Mixing in Pipelines, in: Handbook of Industrial Mixing Science and Practice, (Paul, E. L., Atiemo-Obeng, V. A. and Kresta, S. M., eds), (2004).

Joshi, P., Nigam, K. and Nauman, E., The Kenics Static Mixer: New Data and Proposed Correlations, Chemical Engineering Journal, 59 (1995), 265-271.

Ooi, R. C., Luo, X. Y., Chin, S. B., Bird, N. C. and Johnson, A.G., The Flow of bile in the Human Cystic Duct, J Biomechanics, 37 (2004), 1913-1922.

Reeder, M., Fasano, J. and Myers, K., Characterization of Blending in Static Mixers, Proc. of Mixing XVIII (Pennsylvania, USA.), (2001).

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