A REVIEW OF STUDIES OF HEAT TRANSFER ENHANCEMENT IN TURBULENT DRAG REDUCING SURFACTANT SOLUTIONS

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Abstract

Drag reduction in turbulent flow of hydrocarbons containing small amounts of high polymer was first reported by Toms about 70 years ago. Previously, Mysels and his coworkers had observed similar behavior in solutions of aluminum disoaps. A few years later, drag reduction behavior was observed in dilute aqueous-surfactant solutions in which long wormlike micelles were present. In the late 1970's this phenomenon found its first commercial application when high molecular weight polymer was added to crude oil flowing through the 800-mile Alyeska pipeline. Crude flow was increased by about 25% with no additional pumps.

However high molecular weight polymers are not suited for use in recirculation systems because the high shear encountered in pumps breaks the primary chemical bonds within the polymer chains. The resulting low molecular weight polymer chain fragments are not efficient drag reducers, and they do not reassemble. On the other hand, surfactant micelles are held together by secondary forces and they reform (self-associate) very quickly after break-up in high shear regions (pumps). Thus, they are effective in recirculation systems.

District heating systems are widely used to heat buildings in urban locations in northern Europe and are also found in the US, Canada, Eastern Europe and other locales. These systems circulate hot water and exchange heat with each building thus relieving the buildings of the need for heat sources (furnaces) and the related investment, space, and maintenance required. They generally utilize cheap waste heat from nearby power plants to heat the circulating water. District cooling systems with the same advantages are utilized in some warm climate regions, particularly the United States and Japan. Adding a drag reducing surfactant additive to the recirculating water could decrease pumping energy requirements of these systems by 50% or more.

There is, however, a serious problem with this scheme as the large reduction in friction loss is accompanied by an even larger reduction in heat transport. Thus, to utilize drag reducing surfactant additives in district heating or cooling systems, heat transport must be enhanced in order to transfer heat to or from each building's internal recirculation system.

Investigators have studied a number of heat transfer enhancement schemes to overcome this problem focusing on temporarily destroying the drag reducing micelle structure at the entrance to the heat exchanger using static mixers, honeycombs, other obstructions, ultrasonic radiation, UV radiation of photosensitive surfactant systems, etc. and others have studied altering the turbulent flow pattern in the heat exchanger. While some of these were effective, generally the required energy input was too great for them to be of practical value. These studies will be reviewed here.

1 Introduction

District heating systems are widely used in Northern and Eastern Europe and Japan, and their use is increasing in the United States and Canada. District cooling systems are utilized in some warm climate regions, particularly the United States and Japan.

District heating and cooling (DHC) systems have the advantages of utilizing waste heat from power plants, eliminating the need for individual heating units in each building, freeing up the space they take up, centralizing maintenance, and allowing for one central, efficient heating or cooling unit. Utilizing aqueous drag reducing solutions in place of water as the circulating fluid allows reduction of the pumping energy requirements in the primary recirculating system. Applications in single-building air conditioning systems have achieved 20-60% decreases in pumping power requirements [1].

Surfactants are the preferred type of drag reducing additives as their self-associating wormlike micelles (WLMs) reform rapidly after they break-up under the high shear conditions encountered in the recirculating pumps in the system. Polymer drag reducing additives would be permanently destroyed by the pump(s) and thus become ineffective.

For heat transfer from the primary circulation system to the secondary systems in each building (see Figure 1), efficient heat transfer is required. Unfortunately the reduction in pressure requirements (reduced momentum transport) in drag reduced flow is accompanied by an even larger reduction in heat transport [2].

Heat transfer reduction (HTR) is commonly reported as the

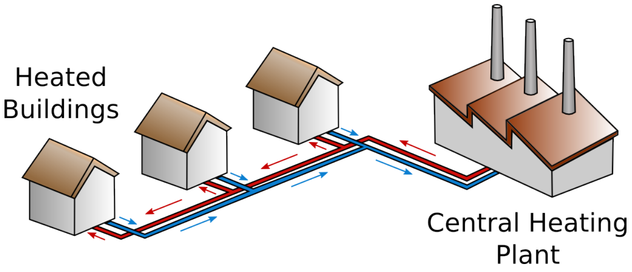

Figure 1. Schematic of district heating system

decrease in the convective heat transfer coefficient compared to the pure solvent (in this case, water).

$$HTR\% = \frac{Nu_{water} - Nu_{measured}}{Nu_{water}} \cdot 100\% \tag{1}$$

The reasons for this reduction in heat transfer have been attributed to two main drag reduction phenomena. First, the wall sublayer in turbulent drag reducing flows is thicker than in Newtonian flows [3] and this thicker sublayer provides greater thermal resistance to radial heat transport. Also, the radial turbulence intensity of pipe flow is markedly reduced in drag reducing flows [4] [5], and thus the radial mixing promoting heat transfer from the wall to the flowing fluid is reduced.

To enhance heat transfer either the drag reducing character of the circulating fluid must be altered, or the structure of the turbulence must be changed by modifying the geometry of the heat transfer surface. Different approaches to one or the other or both of these approaches have been examined for tube-in-tube exchangers. The results of these investigations are described below.

2 Destruction of surfactant wormlike micelle structures

The direct method of enhancing the heat transfer ability of surfactant drag reducing solutions in shell and tube heat exchanges is by destroying their WLM nanostructures at the entrance to the exchanger so that the solution exhibits "water-like" heat transfer behavior while passing through all or most of the exchanger. The WLM structures then reassemble downstream so that drag reducing behavior is regained.

The effects of these techniques to destroy the micelle nanostructures to give heat transfer enhancement depends on their destruction effectiveness and also on the recovery time of the micelles, which can reform in seconds[6] causing the solution to become drag reducing again within the heat exchanger.

2.1 Static mixers and honeycombs

Both static mixers and honeycombs at the entrance to the heat exchanger were studied by Qi et al [6]. These are easy to install, with no moving parts, and so would be convenient to retrofit existing heat exchangers. In those experiments HTR at Reynolds numbers of 20,000 to 50,000 without the devices reached as high as 65%. The insertion of a honeycomb (Figure 2C) at the entrance had little effect on the heat transfer. However, with five elements of plastic Static Mixer B (Figure 2B) HTR was lowered to 40%. The static mixer, while moderately effective caused significant pressure losses thus reducing the advantage of using the drag reducing additive. See Section 3.4 for a discussion of metal Static Mixer A, which utilized a different mechanism of heat transfer enhancement.

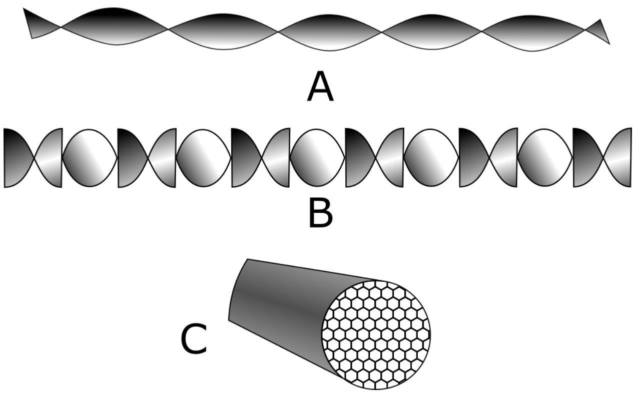

Figure 2. Previously studied static mixing devices [6]: A) twisted tape turbulator - "metal Static Mixer A", B) alternating helix mixer - "plastic Static Mixer B", C) honeycomb

2.2 Ultrasonification

Qi, et al [7] investigated the effect of exposing drag reducing solutions to ultrasonic energy radiation. This broke up the surfactant WLM nanostructures which reduced their turbulence inhibition effect and enhanced the solution's heat transfer ability. HTR was decreased to 24% from 82% with 300 seconds of ultrasonic exposure.

While this technique was effective in enhancing heat transfer, the amount of energy required was large, and imparting such a large amount of energy for micelle breakup to a solution flowing at 1 meter /second or more is not practical.

2.3 Photosensitive counterions

Cationic surfactant drag reducing systems require an appropriate counterion to diffuse their positive charge facing the water phase and promote the growth of long wormlike micelles which modify the structure of the turbulent flow. If the molecular configuration of effective counterions can be altered at the entrance to a heat exchanger to form an ineffective structure, the solution would lose its drag reduction character and show Newtonian properties with greatly enhanced heat transport.

Shi, et al [8] studied light responsive counterions which were very effective as drag reducing counterions with cationic surfactants in *trans* configuration but not in the *cis* configuration. Thus if the drag reducing *trans* configuration counterion could be irradiated with UV light at the heat exchanger entrance and converted to the *cis* configuration, heat transfer would be enhanced in the exchanger. Irradiation with ordinary light would cause a

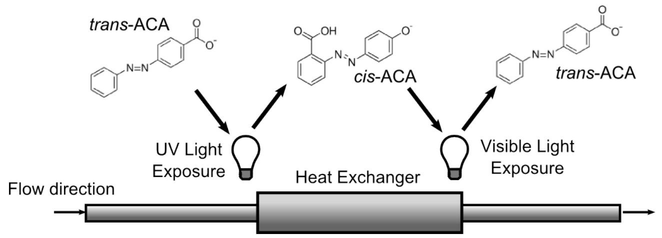

Figure 3. System for switchable drag reduction by photosensitive counterion

reversal back to the drag reducing *trans* configuration. Figure 3 depicts this heat transfer enhancement method.

Despite the potential effectiveness of this approach, it requires more light energy to be absorbed by the solution at both ends of the heat exchanger than can be imparted to the flowing solution in a practical application.

2.4 pH adjustment

pH responsive TLM systems have been developed by use of either pH sensitive surfactants or pH responsive counter ions. Such a chemical system could be used to promote heat transfer in drag reducing surfactant systems with local and reversible pH adjustments by changing the geometry of the micelles [9] or flocculating the TLMs [10].

In the study by Shi et al. [10] using flocculation as a means to control drag reduction, it was shown that DR% could be changed between 80% and -20% over a pH range of approximately 2.0. Furthermore, their system was shown to be stable and reversible even after five pH cycles (from pH ~3 to ~10 and back).

2.5 Excess counterion

Mizunuma [11] studied the heat transfer of viscoelastic and non-viscoelastic drag reducing surfactant solutions with excess counterions both in impinging jet and tube flow. The solutions studied were Ethoquad O/12 with sodium salicylate counterion in varying molar ratios ranging from 1:1 to 100:1. It was found that the effect of excess counterion ratio had little effect on heat transfer in tube flow; however, it was found that the reduction in heat transfer of the impinging jet disappeared with increased Re in the 1800 ppm 1:1 and 760 ppm 3:1 solutions. Also, the 400 ppm 30:1 and 400 ppm 100:1 solutions did not have any loss in heat transfer in the impinging jet flow. It was suggested that the disappearance in heat transfer reduction could be attributed to breakup of the micelles and that a combination of high counterion ratio and high shear at the heat exchanger entrance could lead to effective heat transfer enhancement of surfactant solutions.

3 Modification of turbulent structure

The other approach to enhancing heat transfer in DR solutions is to modify the wall boundary layer and/or to increase radial turbulence intensity and hence radial heat transport. The following approaches have shown moderate or significant heat transfer enhancement.

3.1 Fluted tubes

In a study by Kishimoto et al. [12], cooling of a cationic drag reducing surfactant solution in a concentric tube heat exchanger was enhanced by modifying the turbulent structure with spirally grooved inner tubes. A smooth inner tube and two grooved tubes with different pitches were compared. It was found that the flow velocity range in which drag reduction and heat transfer reduction occurred in both grooved tubes became significantly narrower than that of the smooth tube. The fluted tube with the greater pitch was found to have a lower heat transfer coefficient than water at all velocities tested; however, the heat transfer coefficient of the less pitched of the two grooved tubes in a linear velocity rate range of 1.5 to 2.0 m/s (compared to the typical DHC system operating range of 1.0 to 2.0 m/s) was found to exceed that of water in a smooth tube. The increase in heat transfer was correlated with the increased shear at the tube wall.

The use of a fluted tube heat exchanger to increase heat transfer in cooling of both a cationic surfactant solution (Ethoquad T-1350) and a zwitterionic/anionic surfactant solution (SPE98330) was investigated by Qi et al. [13]. The Nusselt number reported for the Ethoquad T13-50 solution in the fluted tube (Figure 4) was more than 1.2 times that of water in a smooth tube and the ratio of pressure drop of Ethoquad T13-50 solution in the fluted tube to that of water in a smooth tube of equivalent diameter varied from 2.6 to 3.5 from 50 °C to 55 °C. For the SPE98330 solution the heat transfer coefficient was at least 1.4 times that of water in a straight tube with only mild pressure drop penalty. It was suggested that the discrepancy between enhancement results between the two solutions was due to a weaker nanostructure in the SPE98330 solution, allowing shear degradation within the fluted tube.

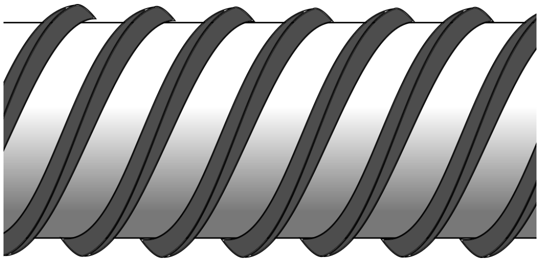

Figure 4. Fluted tube

While the pressure drop penalty for fluted tubes is relatively small [13], retrofitting a heat exchanger to employ grooved or fluted tubes would be impractical in many applications.

3.2 HEV

Since heat transfer is in the normal distance from the wall, Shi, et al. [14] studied the design of a high efficiency vortex (HEV) static mixer designed to promote radial turbulence intensity to enhance heat transfer but which had little effect on axial intensity, so as to minimize axial turbulence dissipation.

This static mixer concept involved forming tabs at the conduit wall inclined at a certain angle to the flow direction such that it enhances heat transfer between the wall and the flowing stream with the minimum amount of turbulent energy dissipation. Figure 5 illustrates the HEV design and Figure 6 shows the amount of heat transfer enhancement compared with static mixers.

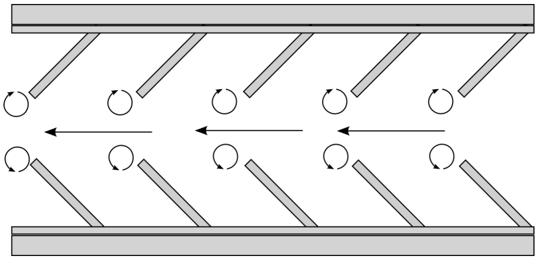

Figure 5. Design of HEV (not to scale)

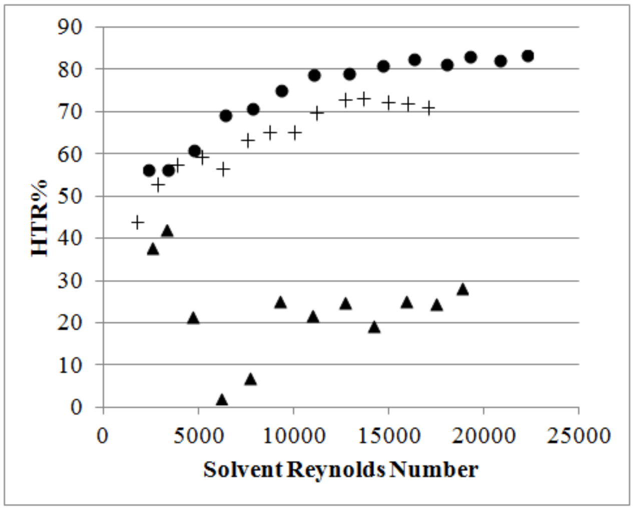

Figure 6. HTR vs Re for HEV (triangles), helical mixer (crosses), and no device (circles)

3.3 Chevron plate heat exchanger

Christensen and Zakin [15] reported that the reduction in heat transfer coefficient for a surfactant drag reducing solution in a chevron plate heat exchanger was 10-65% compared with up to 90+% for the same solution in a tube-in-tube heat exchanger. They attributed this to the chevron providing a pathway that inhibits wall boundary layer buildup. The economic viability of the use of such a plate heat exchanger in a particular application would depend on the capital and maintenance costs for this type of heat exchanger and on the suitability of the plate heat exchanger for the operating conditions.

3.4 Twisted tape turbulator

Qi et al. [6] also tested the effectiveness of another type of static mixer to enhance heat transfer. A metal static mixer wih 15 elements designed to promote swirling flow (Figure 2A) inserted at the entrance to the heat exchanger decreased HTR% to less than 40% but caused a pressure drop across the exchanger of 4x that of water flow with no device.

3.5 Agitated heat exchangers

Our research group recently studied the effects of agitated heat exchangers on the heat transfer coefficients of a surfactant drag reducing solution. These devices were based on common designs of commercial scraped surface heat exchangers.

Using this method, there is no limit to the amount HTR% can be decreased, because the rotation rate of the agitator can be increased until HTR% reaches the desired level, at the cost of increasing power consumption. In this study, HTR% reached as low as -20%. By contrast, micelle destruction methods can only reach a minimum of 0% HTR.

The energy efficiency of the enhancement was better than most previously studied static devices, especially at high Reynolds numbers, and was comparable to the twisted tape turbulator studied by Qi et al. [6].

This approach is discussed in greater detail in another HEFAT 2016 conference paper [16].

4 Conclusion

While turbulent drag reducing solutions reduce pumping energy requirements significantly in recirculating flow systems such as in district heating or cooling systems, heat transfer coefficients are reduced even more. To enhance heat transfer in surfactant drag reducing systems, past studies have focused on destroying micelle nanostructures within the heat exchanger followed by reassociation of micelles and drag reduction recovery downstream or on exchanger designs to modify the structure of the turbulence in tube-tube exchangers. A number of previous studies are described in this paper. While some of the techniques enhance heat transfer significantly, all have disadvantages such as large pressure drops or energy inputs or complexity and cost of implementation. More work is needed in this area to find practical, energy efficient enhancement methods.

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