MIXING TIME IN RHEOLOGICALLY EVOLVING MODEL FLUIDS BY HYBRID DUAL MIXING SYSTEMS

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SUMMARY

Mixing time experiments were performed using a hybrid dual mixing system, which included a helical ribbon impeller (HR) and either a Smith (ST) or Rushton turbine (ST). Xanthan gum solutions (0.14 n 1; 0.001 m [Pa s^n] 12.767) were used as rheologically evolving fluids to evaluate changes in mixing time under non-aerated and aerated conditions (0.40 Fr 0.71, 0.02 Fl 0.06). The helical ribbon agitator and turbine of the hybrid dual mixing system was kept at a constant rotational speed ratio, N_T/N_{HR}=10. Experiments showed that performance of the hybrid mixing system was superior to that of the individual impellers. Flow properties and gassing conditions played an important role in mixing time. While mixing time was practically identical under non-gassed conditions for both the ST-HR and RT-HR mixing systems in low viscosity fluids, differences up to one thousand percent were observed in high shear-thinning fluids. In these fluids, the RT-HR combination exhibited better performance than the ST-HR. In high viscosity fluids, gassing enhanced mixing time particularly when the ST-HR hybrid system was used. Both mixing systems showed similar mixing times under the highest gassed condition evaluated in this work; 1 vvm.

Keywords: Mixing time, hybrid geometry, stirred tanks, gassed conditions, shear-thinning fluids

INTRODUCTION

Mixing plays an important role in chemical, biochemical and food industries. To obtain high quality products and high efficiency processes, mixing must satisfy not only the needs of heat and mass transfer but also the required homogeneity in the vessel in the shortest possible time. It has been widely reported in the literature that mixing conditions are related to product quality in a variety of processes[1-3]. For example, Vlaev et al.[4], evaluating tylosin production by *Streptomyces fradie* in stirred tanks, reported that micro-organisms experience a continuous variation of their immediate chemical environment due to segregation of oxygen and nutrients, which could lead to switching metabolic pathways. Usually, an increase in rotational speed is used in order to eliminate segregation zones. However, excessive energy dissipation, particularly when open impellers are used, could also cause mechanical damage leading to a reduction in productivity[5-10]. An alternative solution to segregation of oxygen and nutrients inside a mixing vessel is offered by a hybrid geometry, composed of a helical ribbon impeller (HR) and a turbine (T)[11,12]. This geometry is particularly interesting for processes where gas dispersion and changes in rheological properties take place. The HR-T system, operating at a rotational speed ratio of 10 (N_T/N_{HR}=10), is capable of eliminating vortices in low viscosity fluids, as well as destroying caverns in high shear-thinning fluids[13]. In the case of gassed conditions, the hybrid dual system dispersed better at a lower Froude number than the turbine alone. This reduction in the minimum Froude numbers for dispersion and re-circulation is highly relevant, in particular for processes involving shear-sensitive materials. It has been reported that the ST-HR achieved better dispersion than the RT-HR[14], which coincides with reports in the literature on individual turbine performance[15,16].

Mixing time is a key parameter for mixing system design. It has been defined by several authors as the time required to reach a specified degree of homogeneity[17-19]. However, data reported in the literature are difficult to compare because homogeneity has been defined on different criteria. In the literature homogeneity has been defined on the basis of two principal approaches, which are closely related to the method used for evaluating mixing time. The first strategy considers the extent of mixing throughout the vessel and assesses mixing time with such techniques as coloration-decoloration[20], thermo-sensible crystals[21], fluorescent spectroscopy with image analysis[22,23], and dual wavelength photometry[24]. The second strategy estimates the degree of ideal mixing in evaluating mixing time. In this case, deviation from ideal mixing is evaluated as non-homogeneity. For that purpose local sensors are distributed throughout the entire vessel. Temperature[25], pH[26,27], fluorescent tracers[28,29], electrical resistivity[30], gamma-emitting particles[31], and magnetic particles[32], are parameters used for evaluating mixing time with probes.

Determining mixing time with local sensors is based on different criteria, which include mainly non-homogeneity. Danckwerts[33] and Michaels and Puzinauskas[34] proposed evaluating non-homogeneity using the variance of the process (s^2) or an estimator of the variance (s^2), while Mohr *et al.*[35] reported the use of the coefficient of variation ($\sqrt{s^2} / \bar{X}$). Käppel[36] and Hiby[37] suggested non-homogeneity parameters based on combinations of initial, local, and final concentrations. This approach was modified by Lundén et al.[38] incorporating several sample points. Jaworski[39], using statistical theory, reported that in a mixing tank it is possible to relate the variance of the volumetric concentration in the total population (s_0^2) to the mean variances in the sub-ranges into which the population was divided exhaustively, according to Equation 1. Total mixing, represented by range 0, includes the effects of macromixing (range I), micromixing (range II) and nanomixing (range III).

$$s_0^2 = s_I^2 + s_{II}^2 + s_{III}^2 \qquad \textbf{(1)}$$

Shaw[40], comparing mixing times obtained with PBT, Rushton turbine and A315-Lightnin impeller, found that mixing time is practically independent of the type of impeller when the specific power input remains constant. Vasconcelos et al.[41], using multiple impellers, reported that an increment in the number of multiple Rushton turbines is not always related to a reduction in mixing time. For example, the mixing time of a double turbine configuration was 57 % lower than that of a three turbine mixing system, confirming Chang´s observations[42] on the claimed, but not well documented, advantage of multiple impellers. Vasconcelos et al.[41] also showed that aeration can have positive, neutral, or negative effects on mixing time and depends on the flow patterns. Micheau et al. [43], working with a double helical ribbon impeller, reported that for low viscosity fluids aeration greatly reduces mixing time. However, an increase in the rotational speed resulted in a small increase in mixing time. These authors illustrated that as shear-thinning behavior increases the influence of rotational speed becomes more significant, whereas, aeration rates did not influence mixing time for this kind of fluid. John et al.[44] compared a single Rushton turbine with dual geometry, which comprised Scaba and Rushton turbines. The latter reduced mixing time up to 90% when the rotational speed was increased.

Differences in mixing times are always related to flow patterns, which depend in turn on hydrodynamic conditions imposed by either the impeller or gassing. Rheological properties also play an important role in hydrodynamic and, consequently, in mixing times. When rheology evolves during the process, designing suitable geometry takes on more relevance, particularly if it is necessary to achieve mixing in a short time. As it has been stated by our research group that hybrid geometries, including a combination of remote and proximity impellers, promote a better flow pattern than individual mixing systems. In this paper, we discuss the effect of rheology, hydrodynamic conditions, and gas feeding rate on mixing time for HR-T systems. We selected a constant rotational speed ratio of 10 (N_T/N_{HR}=10), which has showed acceptable performance for dealing with low viscosity Newtonian and high shear-thinning fluids[13,14].

MATERIAL AND METHODS

The mixing system comprised a flat-bottom vessel made of Plexiglas with two independently driven impellers as shown in Fig. 1. The ST was interchanged with a RT. The geometrical parameters were as follows: tank diameter 0.210 m, liquid height 0.274 m, projected area of the turbine blade 0.016 m, and HR blade width 0.020 m. Working volume was 9.5 L. Viewed from the top the HR rotated clockwise while the T rotated counterclockwise.

Figure 1…

Working fluids included aqueous solutions of Xanthan gum (Keltrol T, Kelco-Merck) as shear-thinning fluids. Solutions were prepared at constant ionic strength by adding 0.1% (w/v) NaCl. The shear-thinning index of the fluids varied from 0.14 to 0.38, the consistency index between 0.32 and 12.77 Pa s^n and their density was 1020 kg/m^3. De-ionized water was used throughout. Gas was fed with a ring sparger 59 mm in diameter and a cross section 9.5 mm in diameter. This device was located 22 mm from the bottom of the tank. Air was supplied through six orifices placed face down, each 0.2 mm in diameter. Air flow rate was measured with an accuracy of 0.2% at full scale by an anemometer (FMA-1828, Omega Inc.), which measures a range of 0 to 50 liters per minute.

Mixing time evaluation was performed using the thermal method. A 2 % volume of the same working fluid, but 40 °C hotter than the liquid in the tank, was added at the upper part of the vessel. Temperature perturbations were measured by thermistors (LO-703, Omega Inc.) using Lab View 3.1 and modules SCX1-1322 and SCX1-1000 (National Instruments Inc.). The average of 10 temperature values was recorded three times per second. The thermistors were distributed inside the vessel as shown in Fig. 2. Thermistor T_1 was located 0.005 m from the wall and 0.090 m below the surface of the liquid, while thermistor T_2 was placed halfway between the shaft and the inner part of the HR. Thermistor T_3 was situated in the same vertical direction as T_1, but 0.047 m from the wall and 0.040 m from underside. Thermistor T_4 was set in direction of the turbine discharge at 0.052 m from the center of the tank and 0.062 m from its bottom.

Figure 2…

The thermistor positions allowed a representative evaluation of temperature distribution inside the vessel during mixing experiments. Thus, the variance due to macromixing in Equation 1 (s_I^2) was estimated by Equation 2.

$$s^2 = \frac{\sum_{i=1}^{n} \left(T_i - T_\infty\right)^2}{n-1} \quad (2)$$

Where T_i represents the local temperature of the n thermistors considered. The criterion adopted for mixing time definition was based on that suggested by Edwards and Baker[45]. This method includes evaluation of the natural variance observed by the probes. It is important to point out that this method has the advantage of avoiding the conflict in mixing time evaluation, which has been reported in literature [46,47], when there is a mixing time distribution in the vessel. Thus, mixing time was considered as the time when the observed temperature variance in the tank after perturbation was lower than the natural variance registered by the sensors, prior to the addition of hot fluid. Figures 3 and 4 show, respectively, the typical evolution of temperature during experiments and determination of mixing time.

Figure 3…

Figure 4…

A generalized Reynolds number (Re_{gen}) was evaluated by Equation 3[48] for the dual geometries studied here.

$$\mathrm{Re}_{gen} = \frac{r \quad N^{2-n} \quad d^2}{m} \quad (3)$$

The above defined Re number may use either the helical ribbon or turbine diameters. Typical results for the operating conditions are shown in Tables 1 and 2.

RESULTS AND DISCUSSION

Hybrid dual geometry and individual performance

It has been reported in a previous work[13] that the hybrid dual geometry can induce three different flow patterns, depending on the speed ratio N_T/N_{HR}. When $N_T/N_{HR} < 10$ there is a segregation of two principal flow patterns, one imposed by the turbine and the other by the helical ribbon agitator. On the other hand, if $N_T/N_{HR} > 10$, the flow pattern is governed practically by the turbine alone. Whereas, for a $N_T/N_{HR} = 10$, a unique, well-distributed flow pattern is observed. These changes in flow patterns also have an influence on mixing time. As an illustration of the superior performance of the hybrid geometry over the individual impellers, Table 1 summarizes experimental mixing time results for a 0.5% Xanthan gum solution under non-gassed conditions.

Table 1…

At the lowest rotational speed used (7.5 s^{-1}), the dimensionless mixing time ($k_m = N_{impeller}\, t_m$) required by the RT was about 20 % of that required by the ST. This is because, when the ST works at a low rotational speed, it does not generate strong re-circulation throughout the vessel, while the RT generates more important axial flows, as pointed out by Mishra and Joshi[49]. However, when rotational speed increased from 7.5 to 10 s^{-1}, the RT reduced k_m by about 35 %, while the ST did so by about 85 %. Thus, k_m was practically the same for the two individual impellers rotating at 10 s^{-1}. Equivalences in mixing time for the turbines studied here have been found previously[15]. A modification of flow patterns is responsible for this effect. Mishra and Joshi[15] reported that RT and ST produce very similar flow patterns when they rotate at high speeds. Also, Shaw[40] reported that the mixing time with RT is very similar to mixing times with five different axial impellers at high rotational speeds.

In the case of HR, it was found that k_m was only around 10% higher than the k_m previously reported for the same impeller[50], even when there was a difference in bottom clearance: 7.9 cm in this work against 2.7 cm for the earlier report. It is important to point out that in all cases the mixing time for the hybrid dual geometry was shorter than the corresponding time for any of the individual agitators. The k_m for both HR-T geometries had values between 8 and 10% of the k_m for the HR, and from 5 to 32% for the turbines alone. These findings suggest that dual geometry is an alternative for dealing with non-Newtonian fluids.

Low viscosity fluids

Table 2 shows the mixing times for low viscosity fluids (water and a 0.1% Xanthan gum solution) under gassed and non-gassed conditions. As shown, non-gassed experiments with water had very similar results; k_m ranged from 9.8 to 11.0 and the average was 10.3 for 36 750 $\leq Re_T \leq$ 49 000 (25 670 $\leq Re_{HR} \leq$ 34 225). Similar values were found by Micheau et al.[43] working with a double helical ribbon and water. These authors reported that k_m decreased from 72 to 10 when Re increased from 30 500 to 84 000 and, for higher Re dimensionless time, remained around 10. On the other hand, it has been reported that open impellers, like the double RT, have a k_m of around 45[47] or even higher, 270 to 310[46]. These results show that the performance of the HR impeller was superior to that of the remote agitators when working with low viscosity fluids at high Re.

Table 2…

In this work, experimental non-gassed and gassed results of k_m for the 0.1 % Xanthan gum solution had an average k_m of 12.3 (Table 2). This value is close to the 10.3 found for low viscosity fluids discussed above. In both cases $Re_{gen\ HR}$ ranged from 69 to 110 and $Re_{gen\ T}$ from 414 to 659. Very similar performance was noted for the double helical ribbon agitators studied by Micheau et al. [43], using scleroglucan solutions as non-Newtonian fluids. These authors reported, for example, that k_m took a value of around 10, when either a 0.5% solution (Herschel-Bulkley model parameters: m=0.135 Pa s^n, n=0.71, t_0 = 6.4 Pa) in the range of 540 $\leq$ Re $\leq$ 800, or a 2.5% solution (m=16.3 Pa s^n, n=0.23, t_0 = 31.6 Pa) in the range of 177 $\leq$ Re $\leq$ 192 was used. The Re values of our mixing-time experiments and those reported by Micheau et al. [43] are clearly in the transition regime; however, the behavior is characteristic of the turbulent regime. It is possible that in these experiments the Re was underestimated. This may be explained if we consider that, in the case of this work, the Re is defined by either the turbine or the helical ribbon impeller. Further work with double hybrid geometry is required to improve definition of the hydrodynamic regime.

Shear-thinning fluids

The dimensionless mixing time results, as a function of Re_{gen} for the hybrid dual geometry with shear thinning fluids (0.14 n 0.38; 0.316 m [Pa s^n] 12.767) under non-gassed and gassed conditions (0.40 Fr 0.71, 0.00 Fl 0.06), are presented in Fig. 5. In the case of non-gassed conditions, it was observed that, as Re increased, k_m decreased, even when Re_{gen}

$_{HR}$<10. This is the typical behavior observed for the transitional regime[51]. Comparing the k_m values obtained for the RT-HR and ST-HR, it is clear that when $Re_{gen\ HR} \leq 3$, the performance of the RT-HR system was superior. This system required only 14 to 25% of the time used by the ST-HR. These findings indicate that the RT-HR system induced a better flow pattern inside the vessel than the ST-HR and point to implications for the design of mixing systems. On the other hand, for $Re_{gen\ HR}$>3, the two systems had very similar performance. This could be attributed to the fact that, as inertial forces become more important than viscous forces, there is an important reduction in effective viscosity, resulting in major improvement of the flow pattern, regardless of the mixing system. Shaw[40] reported that, maintaining the same power input, mixing time was very similar for geometries as dissimilar as PBT, Rushton turbine and A315-Lightnin impellers.

Figure 5…

Gassing has a very important influence on flow patterns and mixing time. Mann[52] and Vasconcelos et al.[41] reported that mixing can be imposed by the impeller, gassing, or a combination of the two. Similar behavior was observed with the hybrid geometries studied here. Comparing non-gassed with gassed conditions in Fig. 5, it is clear that the RT-HR mixer reduced k_m as Fl increased. This reduction occurred because the flow pattern was imposed practically by the gas flow. However, this dominance in the flow pattern is not desirable because it is related to the transition from dispersion to flooding[46]. In fact, as previously reported for high shear-thinning fluids ($n \leq 0.14$), the RT-HR system was flooded under the following hydrodynamic conditions: $0.18 \leq Fr_T \leq 0.71$ and $0.02 \leq Fl_T \leq 0.09$ (Espinosa-Solares et al., 2002), which correspond to the experiments with Re<3. An increase in the hydrodynamic conditions (Re = 4.6) lead to an increment in k_m for the RT-HR mixing system, which indicate the onset of dispersion. Mixing time evaluation at higher Re (7.8 to 108.3) was performed under completely dispersing conditions. In this case, k_m decreased as Re increased. Similar results were obtained with the ST-HR mixing system, except that the ST-HR was flooded at a higher flow rate (1 vvm) than the RT-HR.

It is important to point out that the differences in k_m of up to 1,000 % between gassed and non-gassed conditions with high shear-thinning fluids are related to flooding. Dimensionless time is presented as a function of flow number in Fig. 6 for a high shear-thinning fluid (m=12.767 Pa s^n, n=0.14) and two rotational speeds. It is evident that the RT-HR reduced k_m as Fl increased for both rotational speeds. On the other hand, the ST-HR could handle gassing up to around Fl=0.03 before flooding. These findings confirm that the ST can deal with higher Fl than the RT [15,43].

Figure 6…

CONCLUSIONS

A criterion based on the variance due to macromixing was successfully used for mixing time evaluation with individual and hybrid dual geometries. The mixing times achieved by the T-HR systems (maintaining a rotational speed ratio of $N_T/N_{HR} = 10$) were shorter than the mixing time with the individual impellers (T and HR). For low viscosity fluids, RT-HR was very similar to ST-HR, in terms of dimensionless mixing time. The average k_m of gassed and non-gassed conditions was 12.3, which is similar to the k_m for double helical ribbon impellers (10)[43] and lower to the one reported for turbines (45 to 310)[46,47]. It was observed that, flow properties and gassing conditions played an important role in mixing time. Under dispersion conditions, dimensionless mixing time decreased when the Re increased. There were differences of up to 1,000 % in k_m values with high shear-thinning fluids when gassing rate increased. However, this reduction in k_m was related to the transition from loading to flooding. For high shear-thinning fluids, dimensionless mixing time was shorter for the RT-HR system; however, with the same Fl, the ST-HR system could handle more gassing than RT-HR before becoming flooded. Both mixing systems achieved similar mixing times under the highest gassed condition evaluated in this work (1 vvm). These findings have interesting vessel design implications, particularly for media that depend strongly on short mixing times under either gassed or non-gassed conditions. Thus, the hybrid geometries are alternative devices for processes where rheological properties evolve and also for shear sensitive materials.

Symbols used

Roman letters

d	impeller diameter [m]
D	tank diameter [m]
$Fl = \frac{Q}{N\, d^3}$	Flow or aeration number [-]
$Fr = \frac{N^2\, d}{g}$	Froude number [-]
g	gravitational acceleration [m s^{-2}]
HR	helical ribbon impeller
m	consistency coefficient from the 'power law' and Herschel-Bulkley models [Pa s^n]
N	impeller rotational speed [s^{-1}]
n	behavior flow index from the 'power law' and Herschel-Bulkley models [-]
Q	Gas flow rate [m^3 s^{-1}]
T	Turbine
$\mathrm{Re} = \frac{r\, N\, d^2}{m}$	Reynolds number
$\mathrm{Re}_{gen} = \frac{r\, N^{2-n}\, d^2}{m}$	generalized Reynolds number for 'power law' fluids
RT	Rushton turbine
s^2	variance of a sample
ST	Smith turbine
vvm	gas volume per liquid volume per minute [min^{-1}]

Greek letters

m	viscosity [Pa s]
r	density [kg m^{-3}]
s^2	variance of a population
t_0	yield stress from the Herschel-Bulkley model [Pa]

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support from Autonomous University of Chapingo (UACh), Autonomous University of México (UNAM) and National Council of Science and Technology of Mexico (CONACyT).

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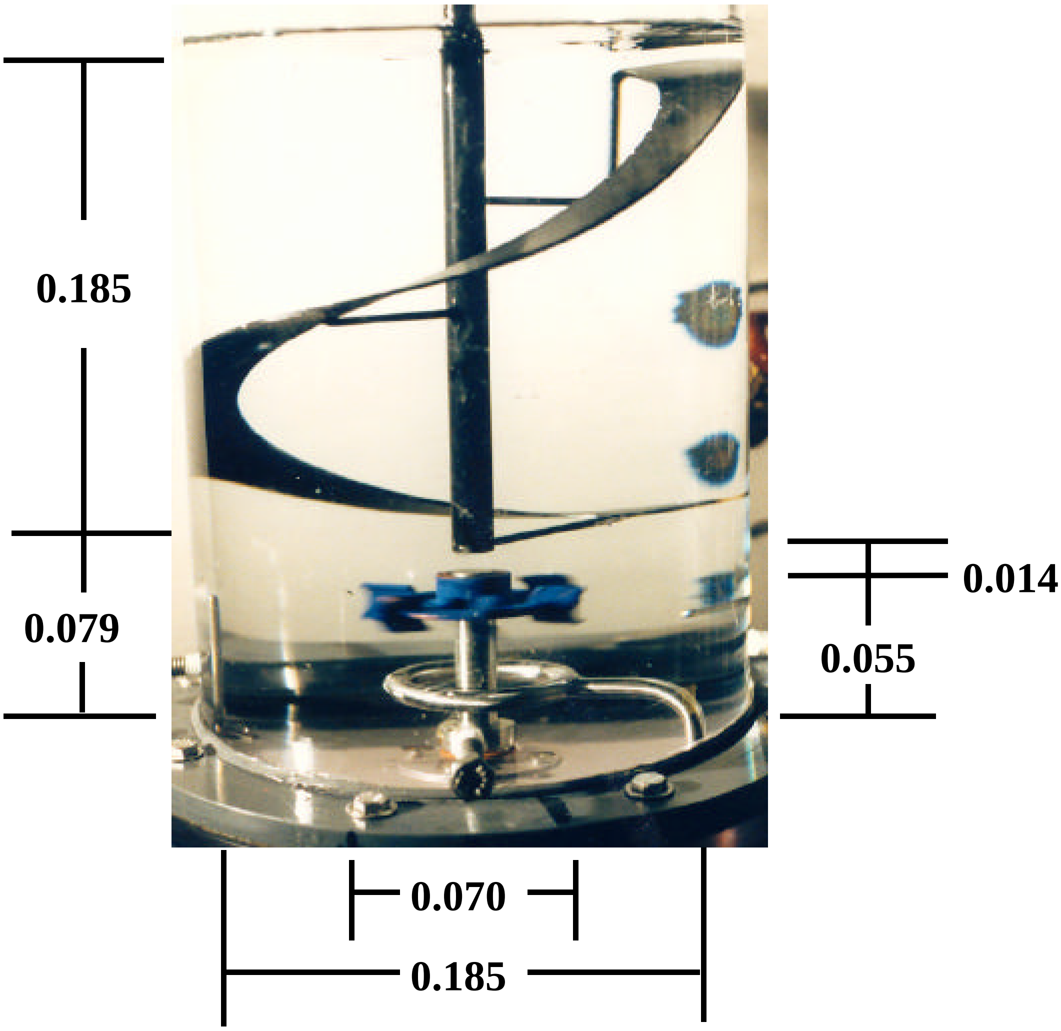
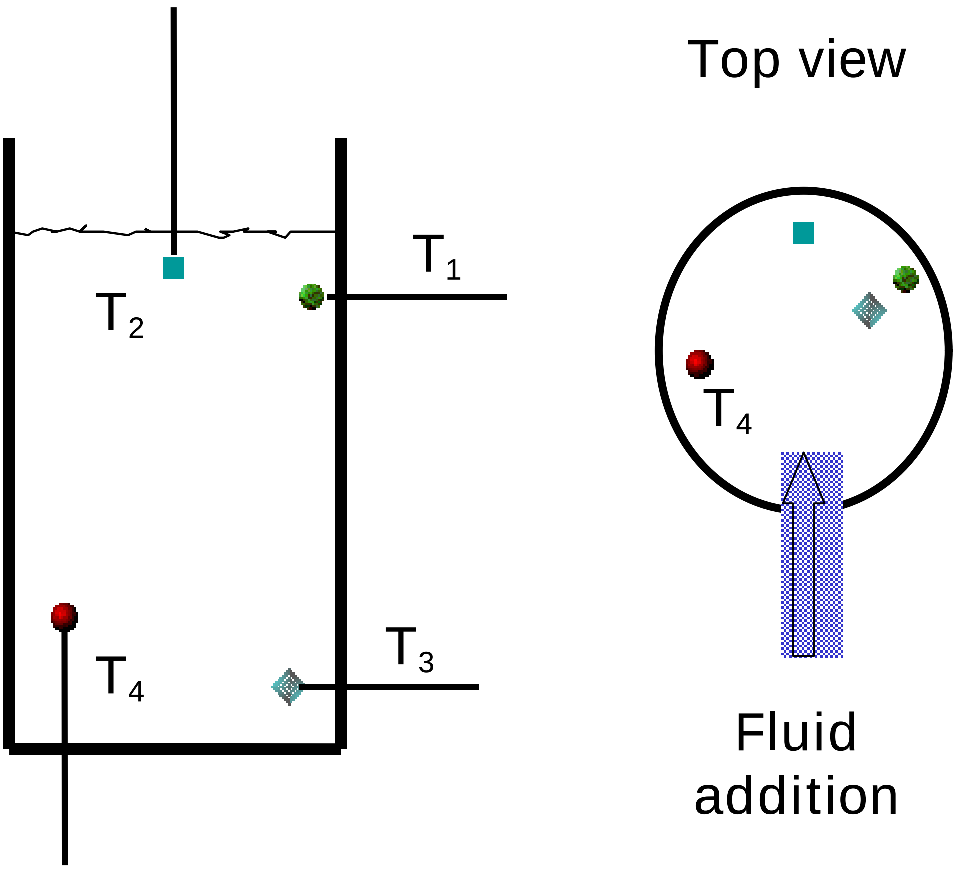
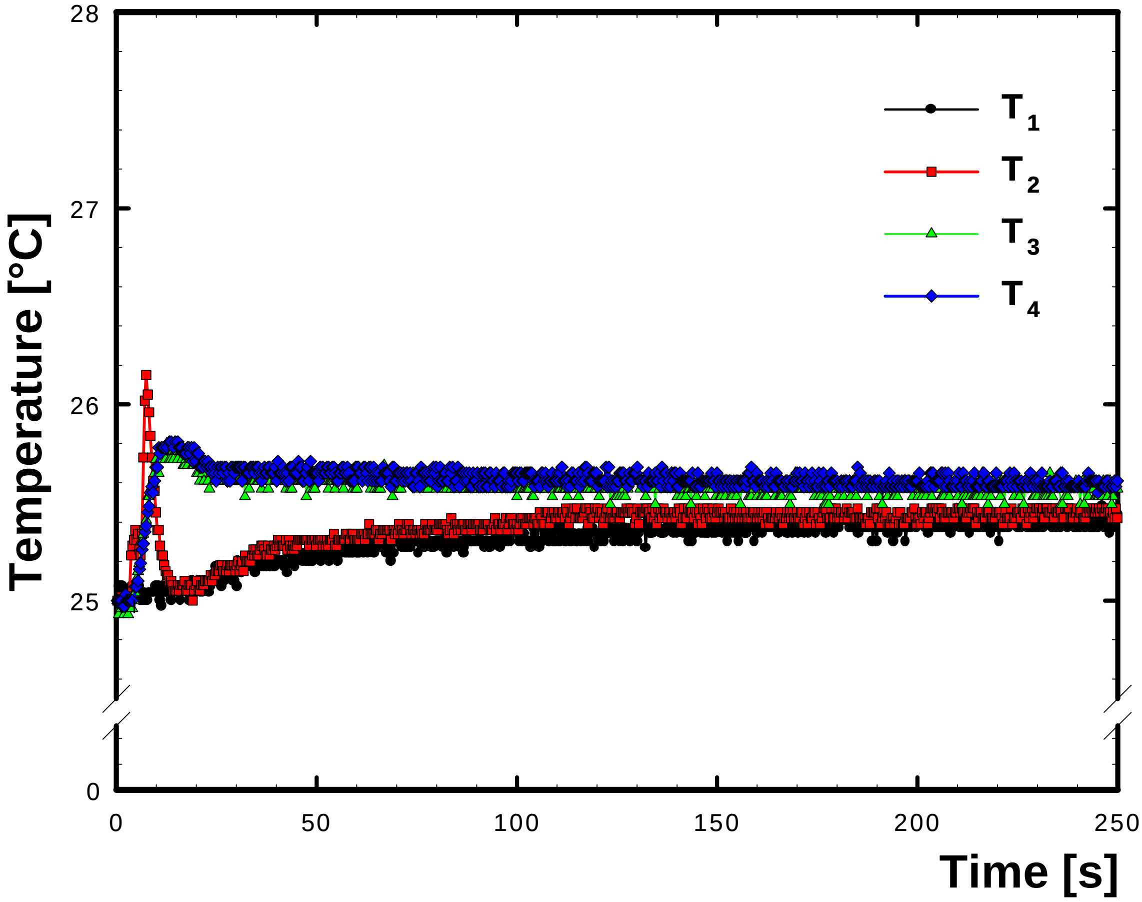
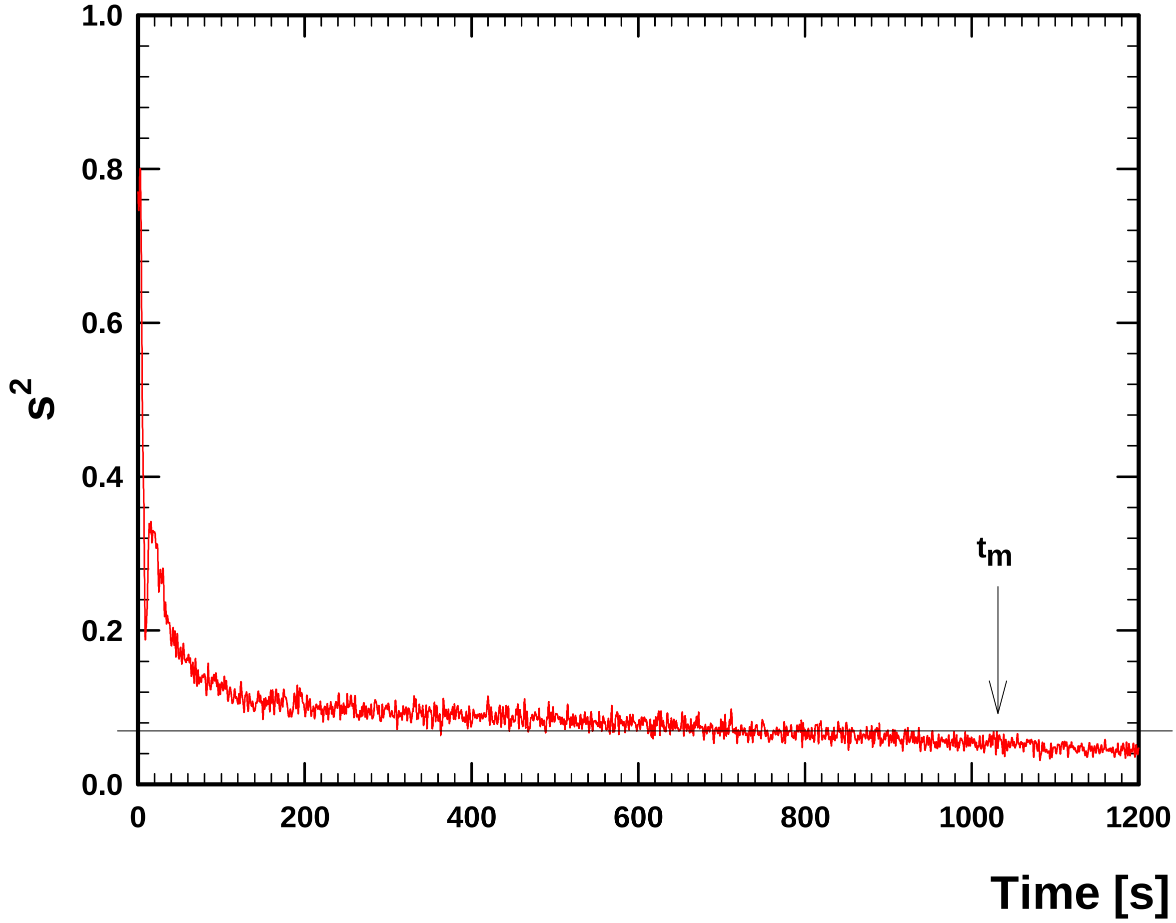
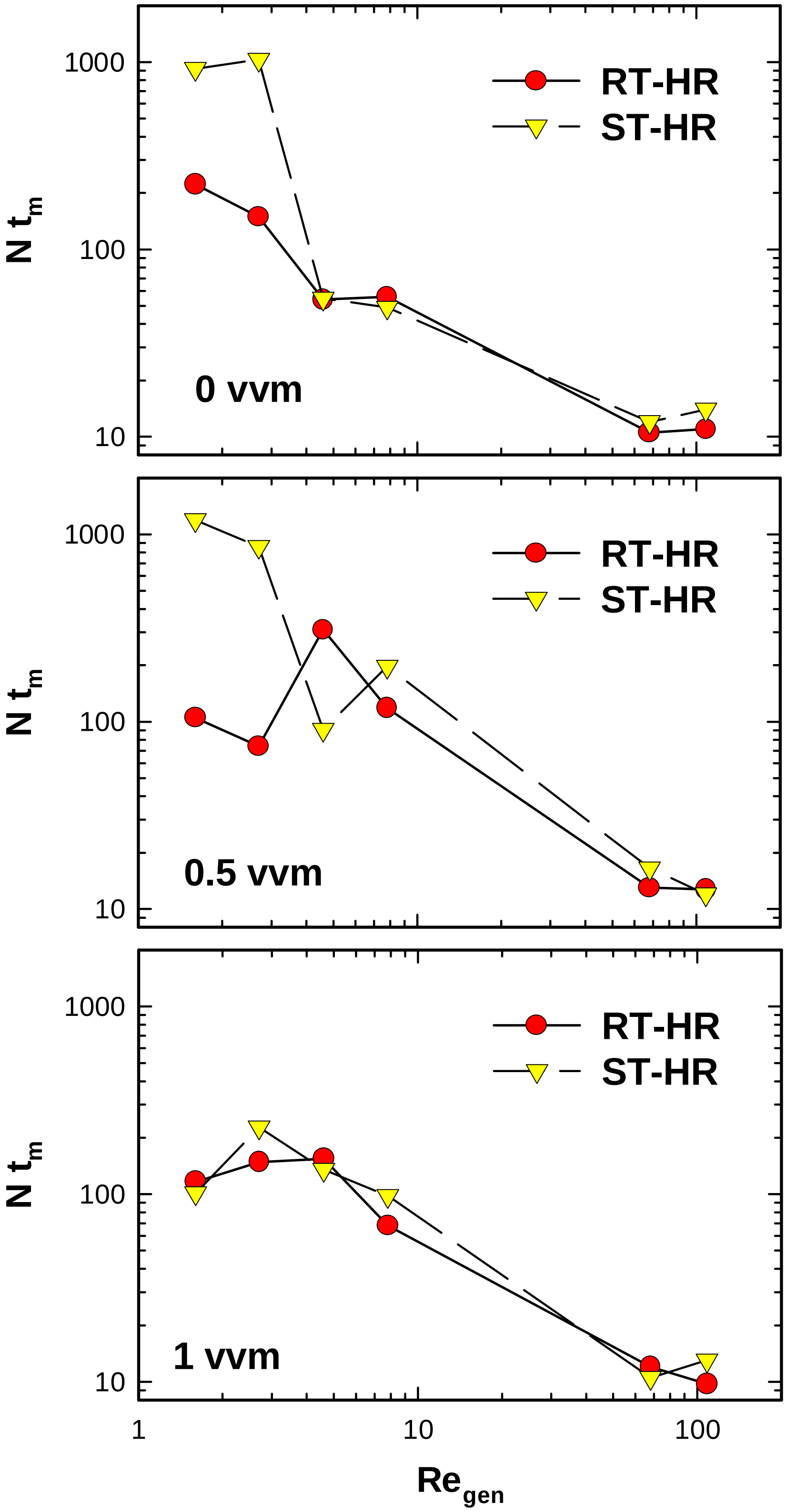

0.185
0.079
0.014
0.055
0.070
0.185


T1
T2
T3
T4
Top view
T4
Fluid
addition

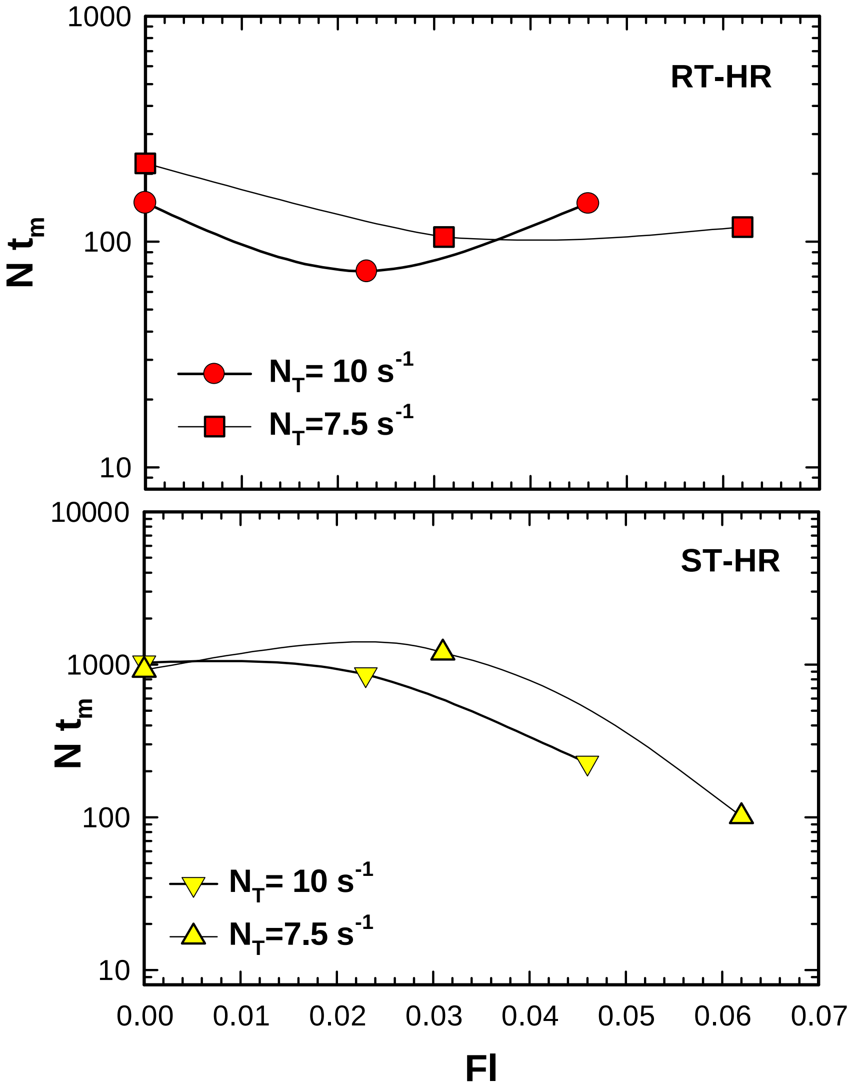

28
27
26
25
0
Temperature [°C]
0
50
100
150
200
250
Time [s]
T1
T2
T3
T4



1.0
0.8
0.6
0.4
0.2
0.0
s2
tm
0
200
400
600
800
1000
1200
Time [s]



RT-HR
ST-HR
0 vvm
0.5 vvm
1 vvm
N t_m
1000
100
10
1
10
100
Re_gen



RT-HR
N t_m
1000
100
10
N_T= 10 s^-1
N_T=7.5 s^-1
ST-HR
10000
1000
100
10
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
FI

Table1

GEOMETRY	N_H $[s^{-1}]$	N_T $[s^{-1}]$	Re_H [-]	Re_T [-]	t_m [s]	$N_H \cdot t_m$ [-]	$N_T \cdot t_m$ [-]
RT	-	7.5	-	44	351	-	2632.5
RT	-	10.0	-	74	178	-	1780.0
ST	-	7.5	-	44	1 500	-	11 250.0
ST	-	10.0	-	74	180	-	1 800.0
HR	0.75	-	4.7	-	767	575.3	-
HR	1.00	-	8.0	-	703	703.0	-
HR-RT	0.75	7.5	4.7	44	72	54.0	540.0
HR-RT	1.0	1.0	8.0	74	56	56.0	560.0
HR-ST	0.75	7.5	4.7	44	73	54.8	547.5
HR-ST	1.00	10.0	8.0	74	49	49.0	490.0

Table 2

Geometry	N_H (s^{-1})	N_T/ N_H [-]	m [Pa s^n]	n [-]	$Re_{gen\ H}$ [-]	$Re_{gen\ T}$ [-]	*vvm* [min $^{-1}$]	Fl [-]	t_m [s]	N·t [-]
HR-RT	0.75	10	0.001	1.00	25 669	36 750	0	-	13	9
HR-RT	1.00	10	0.001	1.00	34 225	49 000	0	-	10	10.
HR-ST	0.75	10	0.001	1.00	25 669	36 750	0	-	14	10.
HR-ST	1.00	10	0.001	1.00	34 225	49 000	0	-	11	11.
HR-RT	0.75	10	0.316	0.38	69.3	414	0	-	14	10.
HR-RT	1.00	10	0.316	0.38	110.5	659	0	-	11	11.
HR-ST	0.75	10	0.316	0.38	69.3	414	0	-	16	12.
HR-ST	1.00	10	0.316	0.38	110.5	659	0	-	14	14.
HR-RT	0.75	10	0.316	0.38	69.3	414	0.5	0.031	17	12.
HR-RT	1.00	10	0.316	0.38	110.5	659	0.5	0.023	13	13.
HR-ST	0.75	10	0.316	0.38	69.3	414	0.5	0.031	12	9.
HR-ST	1.00	10	0.316	0.38	110.5	659	0.5	0.023	22	22.
HR-RT	0.75	10	0.316	0.38	69.3	414	1.0	0.062	13	9.
HR-RT	1.00	10	0.316	0.38	110.5	659	1.0	0.046	14	14.
HR-ST	0.75	10	0.316	0.38	69.3	414	1.0	0.062	12	9.
HR-ST	1.00	10	0.316	0.38	110.5	659	1.0	0.046	11	11.