LASER DIAGNOSTIC ANALYSIS OF COMPLEX FLOW PATTERNS

A New Chemical Engineering Experiment Using Applied Optics

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ABSTRACT

A simple, yet effective, undergraduate experiment has been developed in collaboration between the Chemical Engineering Department and the Optical Sciences and Engineering Program at NJIT. During step change tracer experiments, absorption of red laser light serves as the diagnostic to reveal complex flow patterns in short and long lengths of square cross section clear pipe. The transient absorbance curves constructed from the optical data reveal significant back-mixing in the short flow cell. The long flow cell shows behavior consistent with laminar flow with dispersion in a conduit. This analysis is performed without invoking the complications of the residence time distribution.

INTRODUCTION

The National Science Foundation has declared that applied optics is an "enabling technology," and has stressed that engineering and science curricula should include optics research and education (NSF, 1994). In addition to bulk optics (e.g. lens, mirrors, mounts), modern applied optics experiments provide students with exposure to computers and electronics for data acquisition and manipulation as they explore phenomena in the sciences and engineering (Barat et al., 1998).

Fluid mechanics, of interest to many engineering students, is an important phenomenon that can be investigated optically. For example, the recognition by chemical engineering (ChE) students that real reaction vessels might not be "ideal" due to fluid mechanical issues can be a rude awakening. In some universities, undergraduate ChE programs include in their senior laboratory courses a tubular flow reactor experiment that students expect to be an exercise in ideal "plug flow reactors." The students actually face non-ideal behavior, and are challenged to understand that plug flow behavior is usually limited to turbulent flow in reactor tubes with higher length/diameter ratios.

In this paper, a new undergraduate engineering student experiment is introduced. Laser absorption is used as an optical diagnostic to illustrate the complex and non-ideal flow patterns that arise in short and long conduits with laminar flow. Data are explained in terms of the limiting cases of plug flow and mixed flow without the complexities of the residence time distribution. The

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optical probing offers students an opportunity to make quantitative observations regarding complex fluid flow beyond simple flow visualizations.

EXPERIMENTAL

The overall layout with the short flow cell (7.6 cm long) is shown in Figure 1a. Figure 1b shows the long flow cell (122 cm long) with added mirrors to "telescope" the probing laser beam. The cells are oriented vertically for convenience. On either end of the cells are square plastic flanges, which are held together by threaded support rods (not shown) running the length of the cells. Rubber gaskets between the flanges and the cells are used to seal against leaks. The flow hole in each flange is 0.6 cm diameter. A square cross section (2.5 cm inner side x 0.18 cm wall thickness) for each cell facilitates interrogation by the laser beam.

A red laser beam is used: helium-Neon (632 nm) or diode (~ 650 nm). A neutral density filter, if needed, reduces the incident beam intensity sufficiently to guarantee a linear response from the photodiode detector.

Signals are detected with a lock-in amplifier that is synchronized to mechanical chopper that modulates the laser beam at 1000 Hz. A personal computer, GPIB-interfaced to the lock-in, records the data transferred from the amplifier at 2 Hz. A user-friendly interface program utilizing the Labview® software package allows the students to activate data collection and storage, as well as view a real-time virtual plot of the detector signal.

The cell is fed from either the water or the dye solution station. Calibrated rotameters provide fluid flow rates. Using green or blue dye enhances absorption of the red laser beam. In this work, domestic green or blue food color (e.g. McCormick®) is dissolved in tap or distilled water at a concentration of about 15 drops/liter, which is high enough to achieve strong absorptions, but not so to completely attenuate the beam before it exits the flow cell. Multiple valves and flow bypass lines allow either fluid to be flowing while waiting for introduction to the cells.

In a typical experiment, laser transmission is measured with water flowing. The water source flow is then exchanged for the dye solution flow (positive step change). The pump speeds and rotameters are preset to deliver the same volumetric flow rate of either fluid. The laser transmission signal is recorded with time until a steady value is reached. The cell is then switched back to clear water to flush the cell. This sequence is repeated for several different flow rates, and for three different axial cell locations. If desired, data can be recorded during the flushing-out step. This type of experiment would represent a negative step change.

DATA ANALYSIS

The dye acts as a tracer for diagnosing the flow patterns in the cells. The laser transmission signals are converted to data that are proportional to the tracer concentration using the Beer-Lambert law (Daniels and Alberty, 1975):

\[ \mathcal{A} = \ln \left( \frac{I_0}{I} \right) = \ln \left( \frac{S_x}{S_y} \right) = c_{\sigma} \sigma_{x} L \]

\[ (1) \]
where \( I_0 = \) incident intensity, \( I = \) transmitted intensity, \( S_w = \) recorded signal for water (assuming \( S \) is proportional to \( I \)), \( S_d = \) signal for dye solution, \( d = \) dye absorption cross section (constant), \( L = \) optical path length across cell, and \( A = \) absorbance, which is proportional to dye concentration \( c_d \). Note that \( c_d \) is a mean concentration effectively integrated across the flow cell at any moment.

DISCUSSION

Ideal Limiting Cases

To interpret the absorbance vs. time curves, consider the two limiting cases shown in Figure 2. The plug flow case, corresponding to a plug flow reactor (PFR), shows that dye solution arrives at the optical interrogation point as a constant front without any mixing. The time lags consist of the transit time from valve to flow cell entrance, and the space-time in the cell. Using an absorbance ratio \( A(t)/A_o \), where \( A_o \) corresponds to the full inlet dye concentration, the PFR would show \( A(t)/A_o = 0 \) until the lag time is complete, then a step change to 1.

At the opposite extreme is the mixed flow case corresponding to a continuous stirred tank reactor (CSTR) where the volume is completely homogeneous. Consider a transient dye tracer balance:

\[
v(c_d - c_d) = V \frac{dc_d}{dt}
\]

(2)

where subscript "o" indicates the flow cell inlet condition, \( v = \) volumetric flow rate, \( V = \) mixed vessel volume, and \( t = \) elapsed time. With an initial condition of \( c_d = 0 \) at \( t = 0 \), the vessel tracer concentration transient is:

\[
c_d = c_{do} \left[ 1 - e^{-t/\tau_s} \right]
\]

(3)

where \( \tau_s = V/v \), mean space (residence) time. In terms of the absorbance ratio, Equation 3 for the CSTR becomes:

\[
A(t)/A_o = 1 - e^{-t/\tau_s}
\]

(4)

Short Cell Results

A total of 21 cases were run over a wide range of 7 flow rates and at 3 different axial locations, as listed in Table 1. In all cases, the laser beam laterally entered the cell at the middle position. The lag time for flow through plastic tubing has been removed from all results. Absorbance ratio vs. time plots were generated for all cases. In general, all plots appeared CSTR-like, with some notable features. The data from each run were fitted to the Equation 4 form, resulting in a regressed value of \( \tau_s \). Selected plots are presented here.

Figures 3-5 all correspond to the lowest flow rate (1 cm³/s), with probing at all three positions. Note the periodic dips, most prominent at the lowest location, in the otherwise CSTR-like curve. The dips are likely due to large scale recirculating structure(s), namely shrinking...
volume(s) of "old water." The dips are much less prominent further downstream, suggesting a greater degree of macro-scale of homogeneity.

Figures 6-8 represent a significantly higher flow rate (8 cm$^3$/s). The dips evident at the lower flow rate are gone. The three $\tau_s$ values are essentially the same (average 6.9 seconds), which is nearly the same as the space-time (5.7 seconds) based on total cell volume and flow rate. These similarities are also noted for cases of flow rates of at least 6 cm$^3$/s. This all suggests that the entire cell behaves as a single CSTR at higher flow rates.

Based on a hydraulic (equivalent) diameter for the cell square cross section (2.5 cm), all flows are laminar. The inlet flow experiences a sudden diameter expansion (0.6 cm to 2.5 cm) upon entering the cell, resulting in recirculation zones (Denn, 1980). The sudden contraction upon exiting also creates vortices. Considering its short length, these zones contribute to the overall back-mixed nature of the small vessel. In addition, the length/inlet diameter ($L/D_o$) ratios corresponding to the optical probing range from 2.2 to 10.7. Such low values suggest significant entrance region effects are likely to be felt. The regressed $\tau$ values do not necessarily match the overall vessel $\tau$ values because the regressed values are based on optical data taken inside the conduit, not at the outlet. Therefore, the two values are similar only at higher flow rates where the fluid mechanical energy of the inlet flow causes a back-mixed condition.

**Long Cell Results**

Seven cases were run with the long cell over the same range of 7 flow rates listed in Table 2. The laser beam laterally entered the cell at an axial position 79.4 cm downstream from the entrance. The lag time for flow through plastic tubing was removed, and absorbance ratio vs. time plots were generated.

All plots begin with a zero absorbance time lag, flowed by a CSTR-like curve. Figure 9 shows the absorbance ratio curves for 3 runs: 12.6, 8.4, and 4.2 cm$^3$/s. Visual observation showed that, for the lower flow rates used, the entering dye flow stream remained intact for lengths equivalent to many upstream tube diameters before the formation of long, slow moving vortices along the walls. Further downstream, an arrow-like profile formed, though a dilute centerline stream persisted. At the higher flows, vortices were difficult to discern, and a parabolic-like profile developed fairly soon downstream of the entrance. The dye front noticeably faded as it proceeded up the cell.

To help explain the observations, consider the familiar parabolic velocity profile for laminar flow in circular conduits:

$$u(r) = \bar{u} \left[ 1 - \left( \frac{r}{r_w} \right)^2 \right]$$

where $u(r)$ = linear velocity, $\bar{u}$ = average velocity, $r$ = radial coordinate, and $r_w$ = tube radius. Fluid on the centerline ($r = 0$) will reach a downstream point in one-half the average flow time (space-time). A similar result, based on a more complex relationship for laminar flow in rectangular conduit, is given in Knudsen and Katz (1958). The experimental lag time corresponds to the minimum time for dye tracer to reach the measurement point. Table 2 shows that, for trials 3-7, the lag time is approximately one-half the measurement point space-time. This observation is
consistent with laminar flow. For trials 1 and 2, the lag time is less than one-half the space-time. This is consistent with the visual observation of a centerline flow that appears to persist in the cell.

Since the optical measurements are made only at the centerline position within the tube, they cannot be related to a mixing cup exit dye concentration. For laminar flow, the expected absorbance ratio plot on the centerline would be a PFR result; i.e., a step-change up from 0 to 1.0 at a time corresponding to one-half the location space-time based on the average flow rate. The CSTR-like rise of the curve suggests that mixing is occurring along the centerline. This phenomenon is dispersion (Fogler, 1999), and it accounts for the observed fading of the dye front.

A simple model for dispersion is CSTR's-in-series (Fogler, 1999). Consider two identical CSTR's-in-series, each with a space time $\tau_i$. A transient dye tracer balance on each vessel is performed for a positive step-change in the feed to the first. Borrowing Equation 3 as the transient input to the second vessel, we obtain:

$$c_{d2} = c_{d0} \left[ 1 - \frac{(t + \tau_i)}{\tau_i} e^{-\frac{t}{\tau_i}} \right]$$

(6)

where $\tau_i = $ the space-time of each CSTR, and $c_{d2} = $ the dye concentration exiting from the second CSTR. In terms of the absorbance ratio, Equation 6 for two CSTR's-in-series becomes:

$$\frac{A(t)}{A_0} = 1 - \frac{(t + \tau_i)}{\tau_i} e^{-\frac{t}{\tau_i}}$$

(7)

Acceptable regression fits of the curved portions of the absorbance ratio plots for trials 1-7 were obtained using either a single CSTR (Equation 4), or two CSTR's-in-series (Equation 7). The results are presented in Table 2. A sample plot showing results and a fit for trial 7 is presented in Figure 10. These limited results suggest that, at higher flow rates (though still laminar), the impact of dispersion is less.

CONCLUSIONS AND FUTURE WORK

The use of an optical diagnostic has been successfully demonstrated in an undergraduate experiment in fluid flow in short and long conduits. Over a wide range of flow rates, the macroscopic flow patterns in the short pipe have suggested that it behaves essentially as a CSTR due to internal recirculations even for laminar flow. Thus students observe fluid mechanical mixing without an impeller. Probing of a much longer pipe far downstream of the entrance reveals characteristics consistent with laminar flow and dispersion. These experiments have been analyzed without invoking the residence time distribution. Students learn that flow in a pipe can be more complex than simply laminar and turbulent extremes.
ACKNOWLEDGEMENT

The authors appreciate the support of the Chemical Engineering Department and the Optical Science and Engineering Program at NJIT.

### TABLE 1: Experimental Conditions for Short Cell Tracer Runs

<table>
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<th>Axial (cm)</th>
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**NOTES**

@ Space-time based on flow rate and full flow cell volume

# Space-time based on CSTR-model regression of tracer data

$N_{re}^@$ Reynolds number based on flow cell hydraulic diameter, flow rate, and properties of water
### TABLE 2: Experimental Conditions for Long Cell Tracer Runs

<table>
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</table>

**NOTES**

@ Space-time based on flow rate and cell volume to probe location (79.4 cm downstream from entrance)

# Time lag corresponding to first appearance of dye after entrance into tube

* CSTRs-in-series regression of tracer data – first entry is number of identical CSTRs for best fit, second is individual $\tau_i$

$ Reynolds number based on flow cell hydraulic diameter, flow rate, and properties of water

**REFERENCES**


Figure 1a: Experimental Layout for Short Flow Cell
Figure 1b: Experimental Layout
Showing Long Flow Cell
Figure 2: Ideal Limiting Cases for Tracer Experiment Analysis
Figure 3: Absorbance Profile (Trial 1)

- Experimental
- CSTR-fit (Eq. 4) $\tau = 52$
Figure 4: Absorbance Profile (Trial 8)
Figure 5: Absorbance Profile (Trial 15)
Figure 6: Absorbance Profile (Trial 5)

A(t)/A₀ vs. Time (s)

- Experimental
- CSTR fit (Eq. 4) τ = 7.2
Figure 7: Absorbance Profile (Trial 12)

- Experimental
- CSTR/FT (E=9, τ = 0.7)
Figure 8: Absorbance Profile (Trial 19)

\[ \frac{A(t)}{A_0} \]

- Experimental
- CSTR-fit (Eq. 4), \( \tau = 6.8 \)

Time (s)

0.0  0.2  0.4  0.6  0.8  1.0  1.2

0  10  20  30  40  50  60
Figure 9: Absorbance Profiles (Experimental) for Long Flow Cell Trials 3, 5, 7
Figure 10: Absorbance Profiles (exp. & Eq. 7 fit) for Post-Lag Portion of Long Flow Cell Trial 7