THE STRUCTURE OF HIGHLY IMPINGING FLAMES ON A ROTATING CYLINDER

Colleen Stroud and Melvyn C. Branch, Department of Mechanical Engineering, University of Colorado, Boulder, Colorado, USA and
Mark Strobel and Mike Ulsh, 3M Corporate Research, St. Paul, Minnesota, USA

Corresponding Author, C. Stroud, colleen_stroud@colorado.edu

Flame treatment of polymer films involves exposing one side of a thin film to a laminar, premixed flame while cooling the opposite side with a ceramic-coated metal roller. The flame treatment results in an increase in the wettability of the surface through surface oxidation. The flame environment, therefore, alters the surface of the polymer film and leads to the manufacture of a range of products including adhesive, decorative and medical tape. Interest in flame treatment processes has increased due to improvements in their safety, control, efficiency, ease of operation, and the increased awareness of implementation opportunities. In our previous results we have developed considerable insight into the role of flame chemistry in the flame treatment process. (Branch, et al., 1998; Strobel, et al., 1996; Strobel, et al., 2001; Sullivan, et al., 2000) The results described in the present study focus on the role of fluid mechanics in the flame treatment process to provide a more coherent understanding of the optimum flame treatment conditions and to explain a number of anomalies that can occur.

In order to study the effects of fluid mechanics on the flame treatment environment, we have used a ribbon burner that produces an array of conical laminar premixed flamelets with a cone diameter of approximately 2.5 mm and cone heights from a few millimeters to 20 mm. The fluid flow regimes have been varied by systematically changing the reactant flow velocity, the separation distance between the burner surface and the cylindrical film roller, and the rotational speed of the roller. Of particular interest were highly impinging flames obtained with high reactant flow rates and small burner to roller separation distances.

The research utilized two techniques to characterize the thermal and flow environments created in the flame treatment zone. The first technique was color schlieren imaging to visually describe the thermal gradients generated in the flame treatment zone. The second technique was temperature measurements throughout the flame environment to generate a three dimensional thermal image. These results enabled thermal and flow regime characterizations to be made for the range of experimental conditions.

Figure 1 is a schlieren image showing the highly turbulent and fluctuating flame cones created with high flame powers and a small gap that defines highly impinging flame treatment conditions. The image provides an example of the high level of mixing that is occurring under these conditions indicated by the chaotic changes in color that characterize the thermal gradients. Measurements of the level of flame treatment under these conditions have shown that this high mixing provides for a more uniform treatment environment that in turn, reduces the occurrence of non-homogenous treatment of the polymer film. These are new results derived from the present studies that have influenced the commercial processing of polymer films.

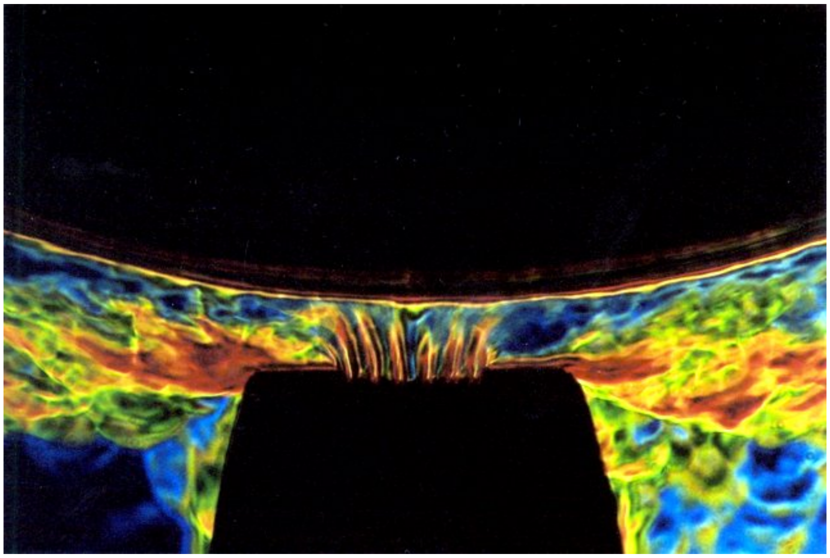

Figure 1 – Schlieren Image of Highly Impinging Flame

The schlieren images under different flow conditions have shown that the flame environment may be laminar, transitional (transitioning between laminar and turbulent), or fully turbulent based on the varying operating conditions. The variables that control the flame flow regime are flame power coupled with combustion induced effects, roller rotational speed, and the gap between the burner and roller surface. An analysis was performed to see if the flame treatment flow regimes established are similar to the published regimes for non-reacting circular jets. It was found that the reacting and non-reacting jets do behave in a similar manner but the reacting jets are shown to be fully turbulent at lower Reynolds numbers due to the occurrence of combustion induced turbulence, a phenomenon that is absent with the inert jet.

Under some flame treatment conditions, unexplained anomalies can occur on the treated surface of the polymer film. One such irregularity is the occurrence of a non-homogeneous treatment of the films, termed “laning.” Laning can be at a physical or chemical level or a combination of both where the treatment is non-uniform across the film and in severe cases is inadequate for commercial use. The understanding of the origin of this phenomenon and devising means to alleviate its occurrence are of major importance to industry.

To investigate the conditions leading to laning, the temperature environment in the vicinity of the film was determined through thermocouple temperature measurements. The highest temperatures are found between ports or openings in the ribbon burner. In contrast, it was found that the temperature decreased significantly directly over the open ports due to the presence of un-reacted fuel and air. The spacing of the temperature peaks was 2.5 mm, which corresponds to the spacing of the laning irregularities observed on the treated polymer film. Figure 2 is a graph of the measured advancing force verses position and is an indicator of the level of treatment that a polymer film has obtained. Figure 3 provides a visualization of the average temperature verses cross-stream position. The matching 2.5 mm interval in minimum temperature and advancing force is very distinct and supports the correlation in results. At higher flame powers, the magnitude of this temperature variation is reduced markedly and the occurrence of laning is correspondingly reduced. This result appears to be due to the increased thermal mixing with high flame power and lends to a more uniform surface treatment. A corollary advantage of high flame power is increased processing speed since the roller rotational speed can be increased while maintaining a uniformly mixed post flame environment.

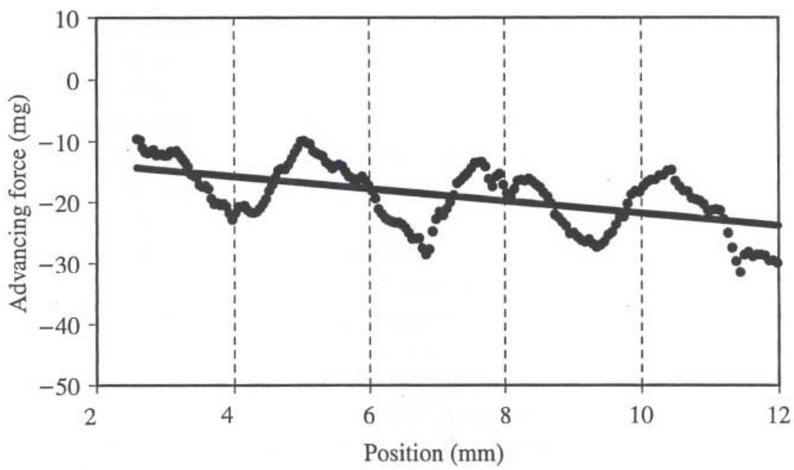

Figure 2 – Advancing Force verses Cross-Stream Position (Parks, 2003)

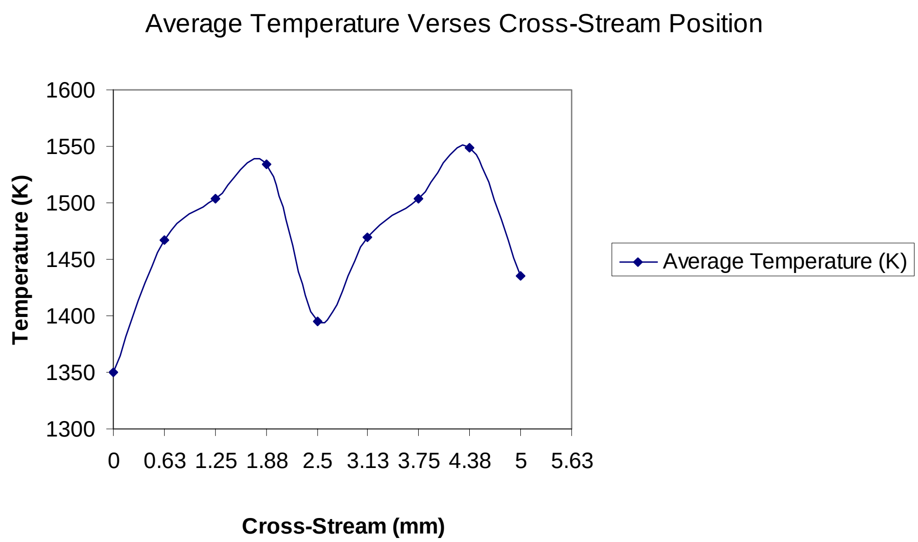

Figure 3 – Average Temperature verses Cross-Stream Position

The flame treatment process involves a complex interaction between flame chemistry, surface oxidation and mixing of flame species above the burner. Our focus in this study has been on the fluid mechanics of the turbulent flow regime that is generated in highly impinging flames on a rotating cylinder. The results described here have provided greater insight into the nature of the flame environment involved in the flame treatment process. These results have been used to improve the speed of the treatment process and the uniformity of treatment.

REFERENCES

Branch, M.C., Sullivan, N., Ulsh, M., Strobel. M., "Surface Modification of Polypropylene Films by Exposure to Laminar, Premixed Methane-Air Flames," Twenty-Seventh Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, pp. 2807-2813, 1998.

Park, J., Lyons, C.S., Strobel, M., Ulsh, M., Kinsinger, M.I., Prokosch, M.J., "Characterization of Non-Uniform Wettability on Flame-Treated Polypropylene-Film Surfaces," Journal of Adhesion Science Tecnologies, Vol. 17, pp. 643-653, 2003.

Strobel, M., Branch, M.C., Ulsh, M., Kapaun, R.S., Kirk, S. and Lyons, C.S., "Flame Surface Modification of Polypropylene Film," Journal of Adhesion Science and Technology, Vol. 10, pp. 551-539, 1996.

Strobel, M., Sullivan, N., Branch, M.C., Jones, V., Park, J., Ulsh, M., Strobel, J.M., Lyons, C.S., "Gas-Phase Modeling of Impinging Flames Used for the Flame Surface Modification of the Polypropylene Film," Journal of Adhesion Science and Technology, Vol. 15, pp. 1-21, 2001.

Sullivan, N., Branch, M.C., Strobel. M., Park, J., Ulsh, M., Leys, B., "The Effects of an Impingement Surface and Quenching on the Structure of Laminar Premixed Flames," Combustion Science and Technology, Vol. 158, pp. 115-134, 2000.