latter quantities will have changing values across the flow (with the exception of plug flow) and thus the observed absorption lineshapes are essentially averages over these U, T profiles. Thus, for all flows more developed than plug flow, $\bar{U}_{\text{meas}}$ is always larger than $\bar{U}$, with the difference increasing as the temperature deficit between centerline and outer radial positions becomes larger. This is because the velocities near the center line of the flow tend to be higher than $\bar{U}$ and the number densities are also higher than $N(\bar{T})$ Thus, these values are overweighted compared to values nearer the wall. As the flow distribution becomes more parabolic (towards fully developed flow), this effect becomes more pronounced, thus a larger correction is required to determine the line of sight average flow velocity.

As described above, $\bar{T}_{\text{meas}}$ is determined from the measured water absorption linewidth. The predicted behavior of the temperature ratio, $\bar{T}_{\text{meas}} / \bar{T}$ is more complex than that of the velocity ratio because the measured temperature is affected by two competing phenomena. Firstly, the density is highest on the center line where the temperature is lowest, thus the absorption at center radial positions is weighted more than that near the wall, making the measured temperature appear cooler than the line of sight average temperature. Alternatively, the effect of the velocity distribution is to make the absorption line shape appear broader, due to the variation in the frequency position of the peak line shifts. This latter effect makes the measured temperature appear warmer than the average temperature.

In order to accurately correct the measured gas temperatures and velocities to account for the effect of the developing flow profile, absorption lineshapes were calculated as a function of flow parameter, velocity, and gas temperature difference between the duct wall and average gas temperature. The calculated lineshapes were analyzed and compared to the average flow profile (Fig. 17) gas temperature and velocity. The ratios of the calculated lineshape temperature to the average flow profile temperature, $\bar{T}_{\text{meas}} / \bar{T}$, and the corresponding velocity ratios, $\bar{U}_{\text{meas}} / \bar{U}$, are used to develop temperature and velocity scaling factors to provide the instrument user with line of sight average measurements of the water vapor number density, $N(\bar{T})$, temperature $\bar{T}$, and velocity $\bar{U}$.

Following the calculation of the average line of sight water vapor number density, and velocity, the water vapor mass flow rate may be calculated using Eq. 11. The resulting mass flow rate does not account for developing velocity flow profile. The line of sight average mass flow rate overweighs the centerline radial positions, which subtend smaller cross-sectional areas of the duct as compared to outer radial positions. To correct the calculated mass flow rate, a mass scaling factor is determined by integrating the velocity profiles shown in Fig. 17. Figure 18 displays the mass scaling factor as a function of the calculated flow parameter (Eq. 12).

TDLAS Applications

TDLAS applications in lyophilization process monitoring have been discussed in recent publications [15–18, 20, 21]. While the authors acknowledge that some of the most important applications of TDLAS will lie in its use in lyophilization