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Analysis of Water Modeling of Air Entrainment

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ABSTRACT

An analysis is reported of the water modeling experiments of Bates et al. (1994) to study air entrainment during pouring of steel. An overview is provided of the relevant flow and design variables that affect air entrainment in the lip pouring experiments. Based on a review of the hydraulics literature, the ways in which changes in the flow variables affect air entrainment are identified. The experimental data are analyzed by examining the effects of the design variables on the flow variables and, hence, air entrainment. It is found that the impingement angle between the jet from the ladle and the sprue is the most significant flow variable which affects air entrainment. A ladle design which produces a large diameter circular jet with least velocity and turbulence, and with a trajectory that causes the jet to impinge on the sprue wall with a minimum angle, would entrain the least amount of air.

INTRODUCTION

Water modeling of the pouring of steel provides a unique opportunity to study air entrainment. Air entrainment during pouring leads to reoxidation of the steel and, ultimately, inclusions in the casting. The use of water as a model fluid allows for the systematic investigation of a large variety of pouring configurations and the direct measurement of the amount of air entrained. Relevant similarity considerations for water modeling of air entrainment in steel pouring and the limitations of water modeling have been reported in a previous study (Beckermann, 1992).

The objective of the present study is to perform an analysis, based on fundamental considerations of hydraulics, of the air entrainment data obtained in the water modeling experiments of Bates et al. (1994) (see these proceedings). First, a review is provided of the relevant flow and design variables that affect air entrainment in a lip pouring system, which is followed by a summary of the test data analyzed here. The reader is referred to Bates et al. (1994) for a detailed description of the experiments and procedures used to obtain the data. Next, an analysis is presented of how changes in the pouring system design cause either an increase or a decrease in the amount of air entrained. The test data are examined in view of this analysis and conclusions are made with respect to the relative importance of the various design variables in controlling air entrainment. The present analysis is limited to lip pouring ladles; other available test data will be examined in the near future.

BASIC DEPENDENCIES

Air entrainment in the water modeling experiments involving lip pouring ladles is primarily controlled by the flows in the ladle, the velocity and nature of the water jet between the lip and the sprue, and the way the jet impinges on the sprue wall. The main flow variables are

- jet velocity, v
- jet diameter, d
- jet cross-sectional shape, S
- approach-flow turbulence, Tu
- impingement angle, Θ (with respect to sprue wall)

The jet velocity is primarily determined by the free-fall height, h, measured from the lip to the water level in the receiving tank below the sprue, according to

$$v = \sqrt{2gh} \quad (1)$$

The jet diameter is a measure of the cross-sectional area of the jet, A_c. For example, for a circular jet

$$A_c = \pi d^2 / 4 \quad (2)$$

The cross-sectional area, in turn, depends directly on the water flow rate, Q, as

$$A_c = Q/v \quad (3)$$

The jet shape, S, and the approach-flow turbulence, Tu, depend primarily on the lip design and the flow inside the ladle, respectively, both of which are difficult to quantify. The impingement angle, Θ, is determined by the trajectory of the jet relative to the sprue and on which side of the sprue the jet impinges (Fig. 1).

A review of the hydraulics literature shows that, generally, the rate of air entrainment increases with increasing v, Tu, and Θ (Ervine and Falvey, 1987; Ervine et al., 1980; Renner, 1975), and decreasing d. Furthermore, the smaller is the jet perimeter (circular in the limit), the lower is the air entrainment.

The water modeling experiments consisted of several changes in the design variables (i.e., sprue length, pouring rate, ladle depth, lip position, sprue angle, ladle design). The way these changes affect air entrainment depends on how the above listed flow variables are affected by the design variables. The design variables investigated and the corresponding flow variables which are primarily affected are summarized in the following.

Design Variable	Flow Variables
Ladle design (type of ladle, lip shape)	d, S, Tu and Θ
Ladle depth	Θ
Lip position (fixed or variable)	v and Θ
Pouring rate	d and Θ
Sprue length	v
Sprue angle	v and Θ

TEST RESULTS

The air entrainment data obtained by Bates et al. (1994) are summarized in Tables 1, 2, and 3. In all, five ladle designs (SR1, Pelton, Universal, Quadrant, and FOSECO), four sprue designs (sprue angle = 0 and 30 deg; sprue length = 5 and 10 in), two pouring rates (maximum and slow), two ladle depths (full and half), and two lip positions (fixed and variable) were examined. Not all combinations were tested (see Table 1). Table 2 summarizes the test data for the lip designs examined on the FOSECO ladle (short nonteapot, long nonteapot, short teapot, long teapot), while Table 3 contains the air entrainment data for the square lip design tested on the Quadrant ladle.

The reader is referred to Bates et al. (1994) for a description of the various designs and an analysis of the statistical significance of the air entrainment data.

ANALYSIS

Effect of Sprue Length

The sprue length primarily affects the jet velocity. The longer the sprue length, the higher the jet velocity. Thus, air entrainment is expected to increase with sprue length, which indeed is the case in all tests (Figures 2a through 2f), except for the FOSECO long teapot ladle at the slow pouring rate in the slanted sprue (see Fig. 2e). The only reason for the inconsistency appears to be that the impingement angle for the short sprue was larger than that for the long sprue.

Effect of Pouring Rate

The pouring rate primarily affects the jet diameter and the jet trajectory (impingement angle). The higher the pouring rate, the larger the jet diameter and the impingement angle (see Fig. 1a). The two variables (jet diameter and impingement angle) have opposite effects on air entrainment. The water tests to examine the effect of the pouring rate we conducted only for the FOSECO ladle with the slanted sprue; the results are presented in Figure 3. For the short lip type, the effect of the pouring rate is small, less than or equal to about 0.007 cft. For the long lip type, the air entrainment is smaller for the slow pouring rate than for the maximum pouring rate. This indicates that the effect of the impingement angle is more significant than that of the jet diameter.

Effect of Ladle Depth and Lip Position

The ladle depth affects the impingement angle and the jet velocity (assuming a constant pouring rate). For the fixed lip position, the jet velocity does not change with ladle depth, but the impingement angle decreases with increasing ladle depth (see Fig. 1b). Consequently, one would expect air entrainment to increase with decreasing ladle depth. For the variable lip position, the jet velocity increases (drop is more with large ladle depth) and the impingement angle decreases with increasing ladle depth. These two variables have opposite effects on air entrainment.

The effect of ladle depth was studied only for the SRI and Pelton ladles; the results are shown in Figures 4a to 4c. For the fixed lip position, air entrainment, both for the SRI and Pelton ladles, decreases with ladle depth, as explained above, except for the Pelton ladle with a vertical short sprue in which air entrainment remains unchanged. For the variable lip position, air entrainment increases with ladle depth, except for the Pelton ladle with a slanted short sprue in which air entrainment slightly decreases with the ladle depth. These results indicate that in most cases the effect due to an increase in the jet velocity is larger than that due to a decrease in the impingement angle.

Effect of Sprue Angle

The sprue angle affects the jet velocity due to a change in the drop height and the impingement angle. The larger the sprue angle, the smaller the jet velocity and the smaller (or larger) the impingement angle, if the jet impinges on the far side (or near side) of the sprue (see Fig. 1c). If the jet impinges on the far side of the sprue, air entrainment decreases with increasing sprue angle, as was the case for the FOSECO ladle (short nonteapot lip, long nonteapot lip, and short teapot lip) as shown in Figure 5a, for the Quadrant (square lip) as shown in Figure 5b (except for the angled channel with a short sprue), and for the Pelton ladle (except for fixed lip position and half ladle depth) as shown in Figure 5c. If the jet impinges on the near side of the sprue, air entrainment increases with increasing sprue angle (assuming the effect of impingement angle is more significant than that of the jet velocity), as was the case for the Pelton ladle (fixed lip position and half ladle depth) as shown in Figure 5c, for the SRI, Universal, and Quadrant (Pelton lip) ladles as shown in Figure 5d, for the Pelton ladle (variable lip position) as shown in Figure 5e, and for the FOSECO ladle (long teapot lip) as shown in Figure 5f.

It should be pointed out that the pouring rates for the slanted sprue were significantly less than those for the vertical sprue. The effect of the pouring rate has been discussed above.

Effect of Ladle Design

The ladle design affects d, S. Tu, and Θ. Four lip designs of the FOSECO ladle were tested. The results in Figure 6a for the short nonteapot lip versus short teapot lip, and in Figure 6b for the long nonteapot lip versus the long teapot lip, show that the FOSECO ladle is better with a nonteapot lip than with a teapot lip. The comparison of a short nonteapot lip to a long nonteapot lip, as shown in Figure 6c, suggests that a long nonteapot lip entrains less air. Among the four lip designs, the long nonteapot lip ladle performs the best. The nonteapot lip ladle is better than the teapot ladle due to less turbulence in the former than in the latter.

Five lip designs of the Quadrant ladle were tested. The results presented in Figure 7 show that a slot lip ladle performs better than the others. This is due to less turbulence in the slot-lip ladle.

The results of five ladles (slot lip Quadrant, long nonteapot lip FOSECO, Pelton, Universal, and SRI) are compared in Figure 8a for the slanted sprue and in Figure 8b for the vertical sprue. The slot lip Quadrant ladle with the slanted sprue is significantly superior to the others; the SRI and the Universal ladles are the worst. The Quadrant ladle is also better for the vertical sprue (except one data point for the long sprue) than the others. The Pelton and FOSECO ladles are the worst for this case.

The ladle design affects so many flow variables that it makes it difficult to provide justification for the performance of a ladle.

CONCLUSIONS

Among the ladles examined in the water modeling tests, the slot lip Quadrant ladle entrains the least amount of air. The jet from this ladle must have small turbulence and its trajectory makes a small impingement angle with the sprue walls.

Among the flow variables, the impingement angle appears to be the most significant variable which affects the air entrainment.

A ladle design which produces a large diameter circular jet with least velocity and turbulence and with a trajectory which impinges on the sprue wall with a minimum angle would entrain the least amount of air.

REFERENCES

C.E. Bates et al., “Water Modeling Tests of Air Entrainment in Steel Pouring,” 1994 SFSA T&O Conference, Chicago, IL, (see these proceedings), 1994.

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D.A. Ervine and H.T. Falvey, “Behavior of Turbulent Water Jets in the Atmosphere and in Plunge Pools,” Proc. Institute of Civil Engineering (London), Part 2, Vol. 83, 1987.

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J. Renner, “Air Entrainment in Surface Rollers,” Symposium on Siphons and Siphon Spillways, BHRA (Cranfield), London, 1975.

Table 1 - AIR ENTRAINMENT DATA (CFT)

Variables	SRI	Pelton	Univer slot lip	Quad	Pelton lip
		LADLE DESIGNS			
VLP; FLD; LSL; 0	.274	.197	.230		
VLP: HLD; LSL; 0	.184	.197			
VLP; FLD; SSL; 0	.198	.168	.216		
VLP; HLD; SSL; 0	.169	.166			
FLP; FLD; LSL; 0	.165	.197	.162	.186	.192
FLP; HLD; LSL; 0	.177	.216			
FLP; FLD; SSL; 0	.140	.167	.147	.081	.148
FLP; HLD; SSL; 0	.167	.167			
VLP; FLD; LSL; 30		.214			
VLP: HLD; LSL; 30		.209			
VLP; FLD; SSL; 30		.187			
VLP; HLD; SSL; 30		.208			
FLP; FLD; LSL; 30	.201	.171	.201	.106	.199
FLP; HLD; LSL; 30		.220			
FLP; FLD; SSL; 30	.162	.140	.161	.062	.176
FLP; HLD; SSL; 30		.201			

FLP = Fixed Lip Position; VLP = Variable Lip Position
FLD = Full Ladle Depth; HLD = Half Ladle Depth
LSL = Long Sprue Length; SSL = Short Sprue Length
0 = Zero Sprue Angle; 30 = Thirty Sprue Angle

Table 2 - AIR ENTRAINMENT DATA (CFT) for FOSECO LADLE

	LIP SHAPE			
	Short Lip		Long Lip	
Variables	Nonteapot	Teapot	Nonteapot	Teapot
FLD;STD;SSL;Max;0	.200	.208	.169	.165
FLD;STD;SSL;Max;30	.149	.195	.109	.255
FLD;STD;LSL;Max;0	.220	.229	.205	.209
FLD;STD;LSL;Max;30	.182	.206	.138	.273
FLD;STD;SSL;Slo;30	.151	.200	.096	.217
FLD;STD;LSL;Slo;30	.175	.201	.116	.173

FLD = Full ladle depth; HLD = Half ladle depth; STD = Standard throat size; LRG = Large throat size;Max = Maximum pouring rate; Slo = Slow pouring rate; 0 = Zero sprue angle; 30 = Thirty sprue angle

Table 3 - AIR ENTRAINMENT DATA (CFT) for QUADRANT LADLE SQUARE LIP SHAPE

Variables	
Sho;SSL;0	.125
Sho;SSL;30	.112
Sho;LSL;0	.191
Sho;LSL;30	.129
Ang;SSL;0	.122
Ang;SSL;30	.130
Ang;LSL;0	.206
Ang;LSL;30	.134
Lon;SSL;0	.151
Lon;SSL;30	.144
Lon;LSL;0	.192
Lon;LSL;30	.176

Sho = Short channel length; Ang = Angled channel length; Lon = Long channel length; SSL = Short sprue length; LSL = Long sprue length; 0 = Zero sprue angle; 30 = Thirty sprue angle

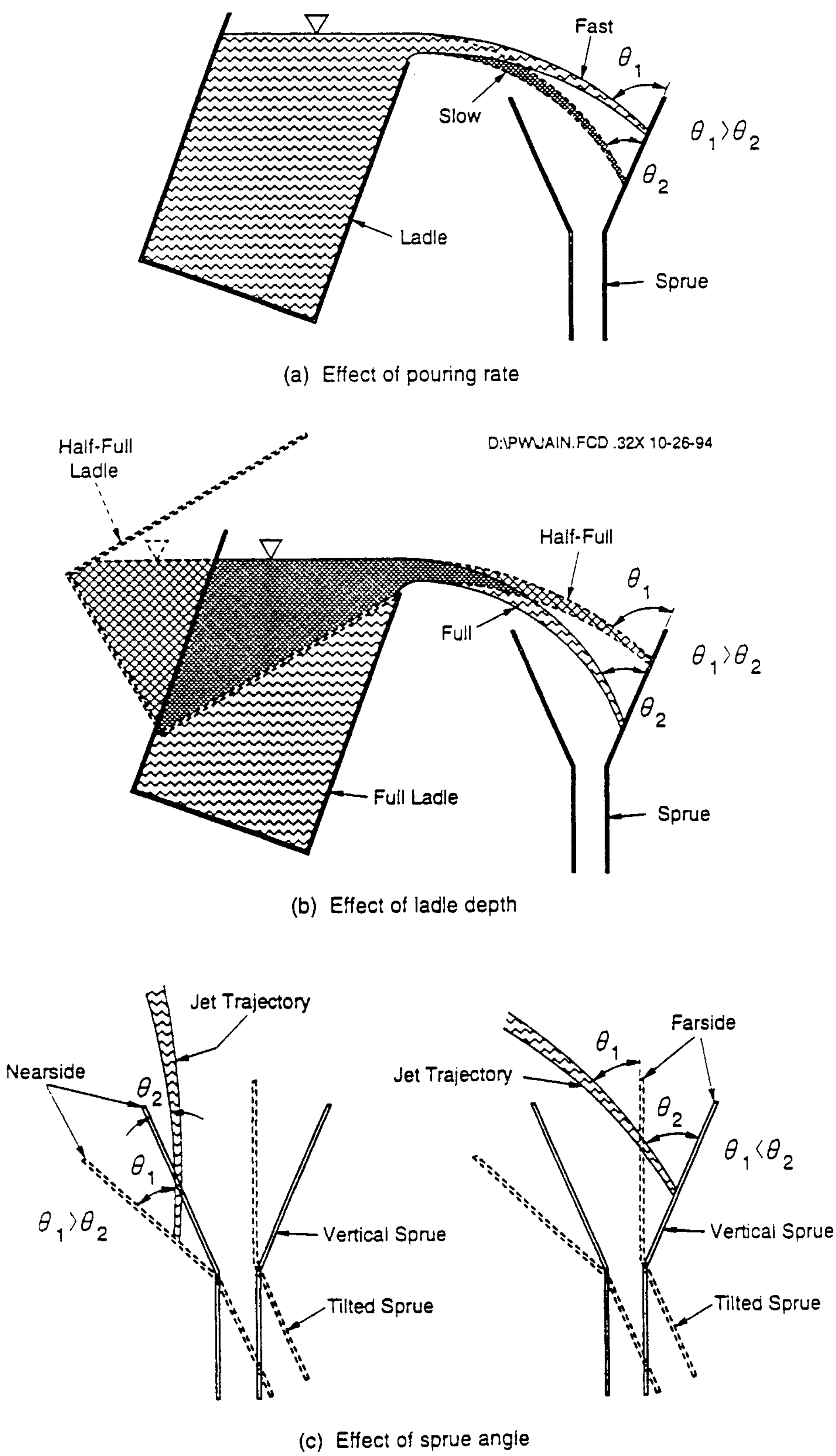


Figure 1 Effect of design variables on impingement angle

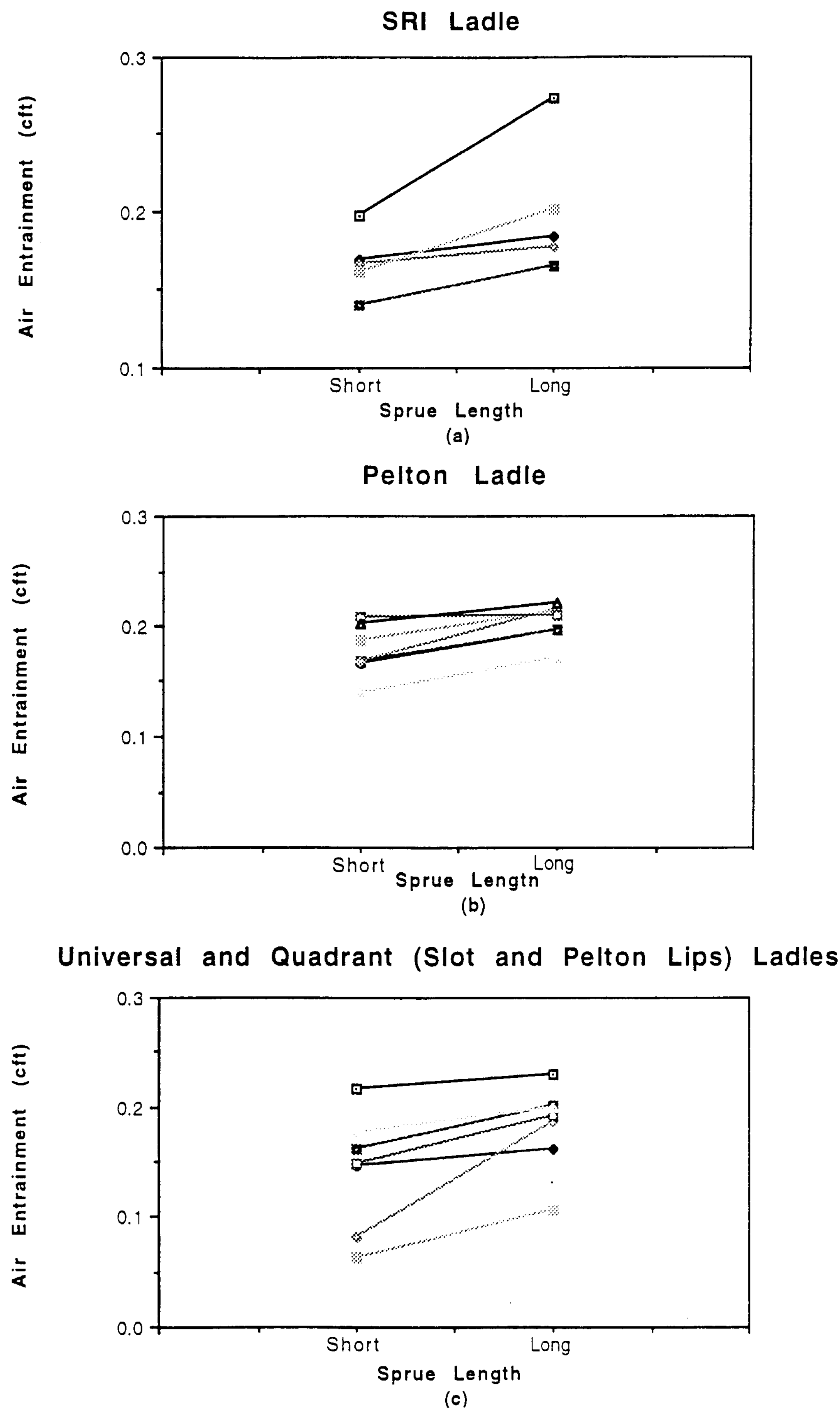


Figure 2 Effect of sprue length on air entrainment

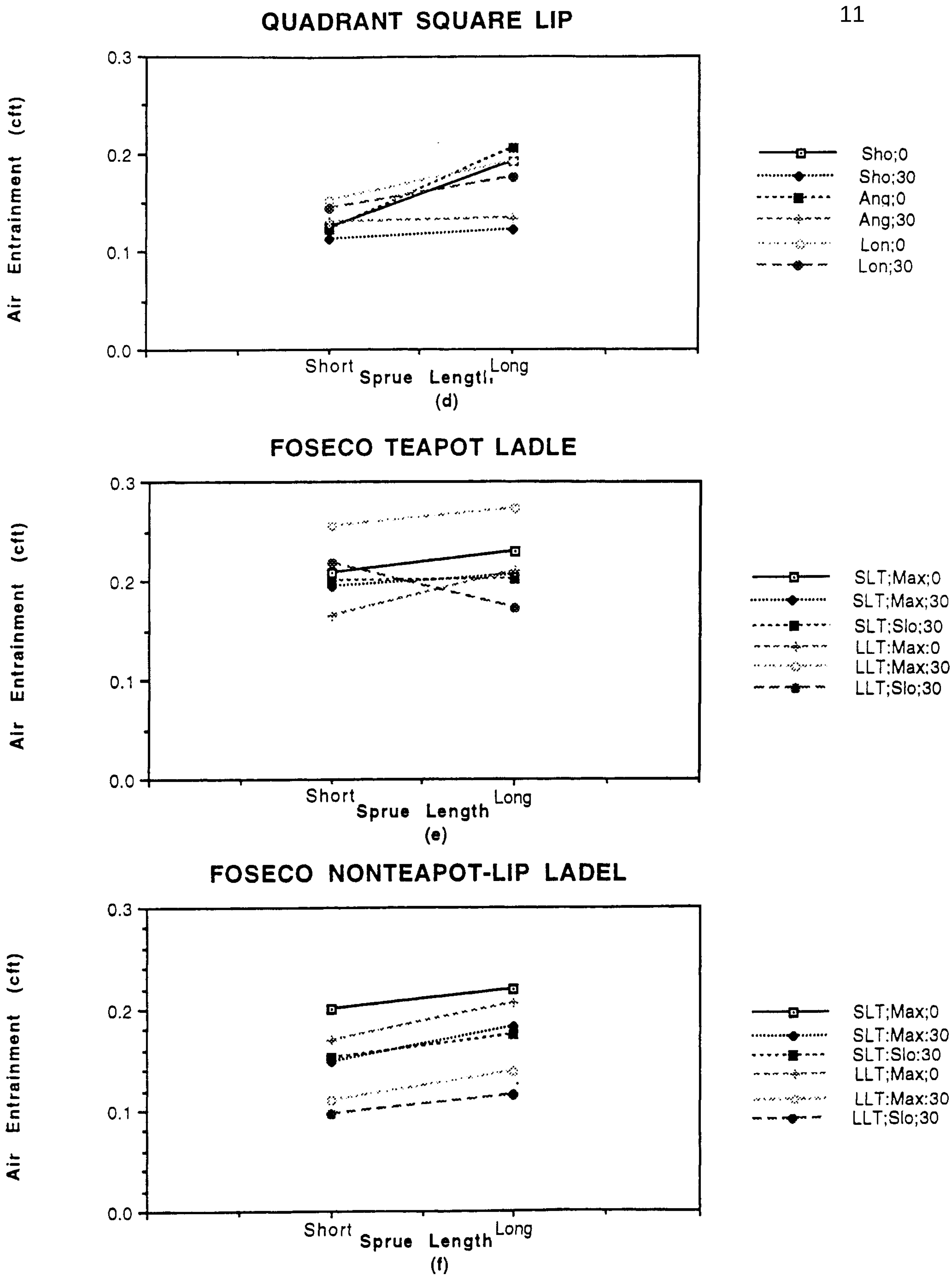


Figure 2 (Continued)-Effect of sprue length on air entrainment

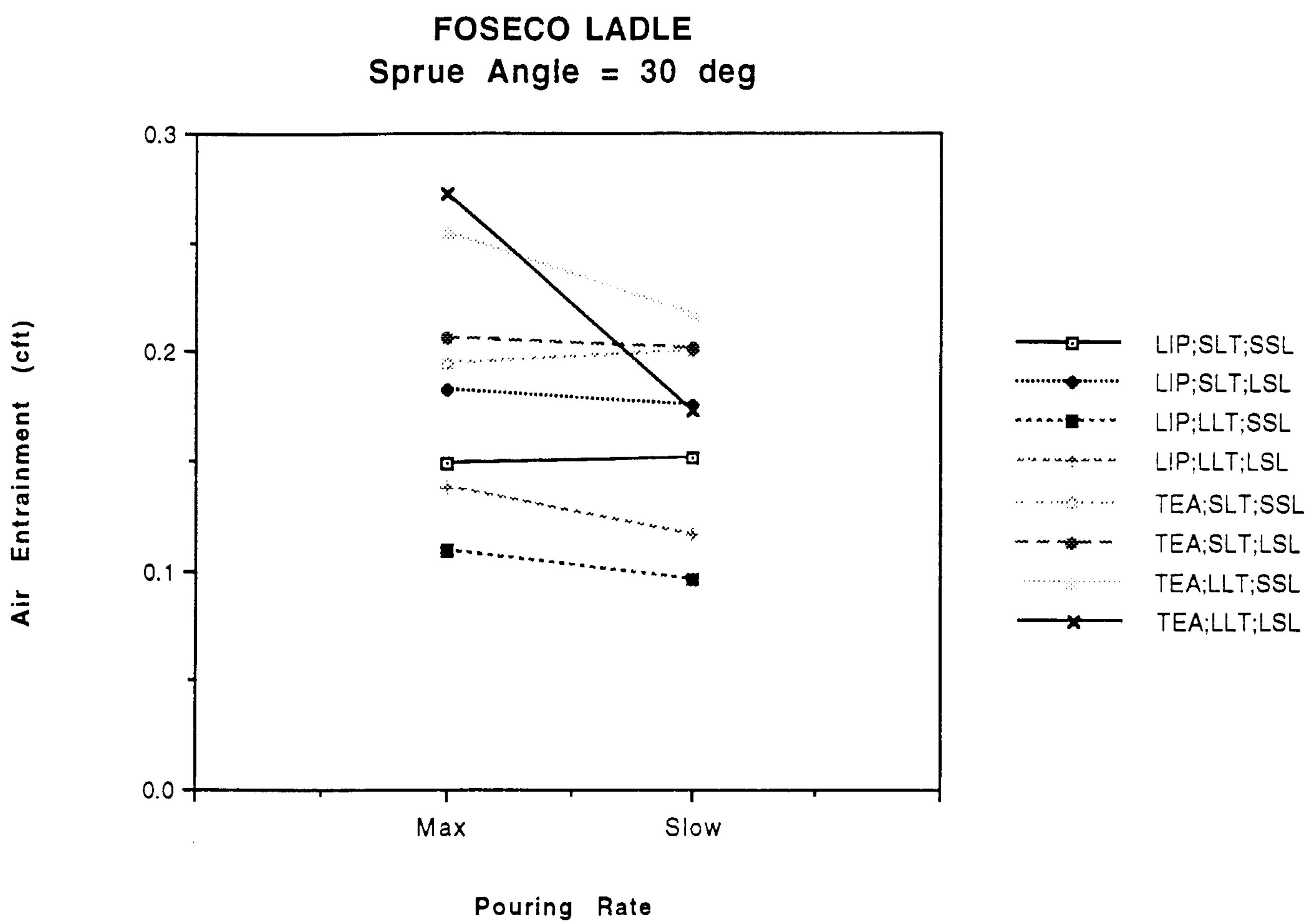


Figure 3. Effect of pouring rate on air entrainment.

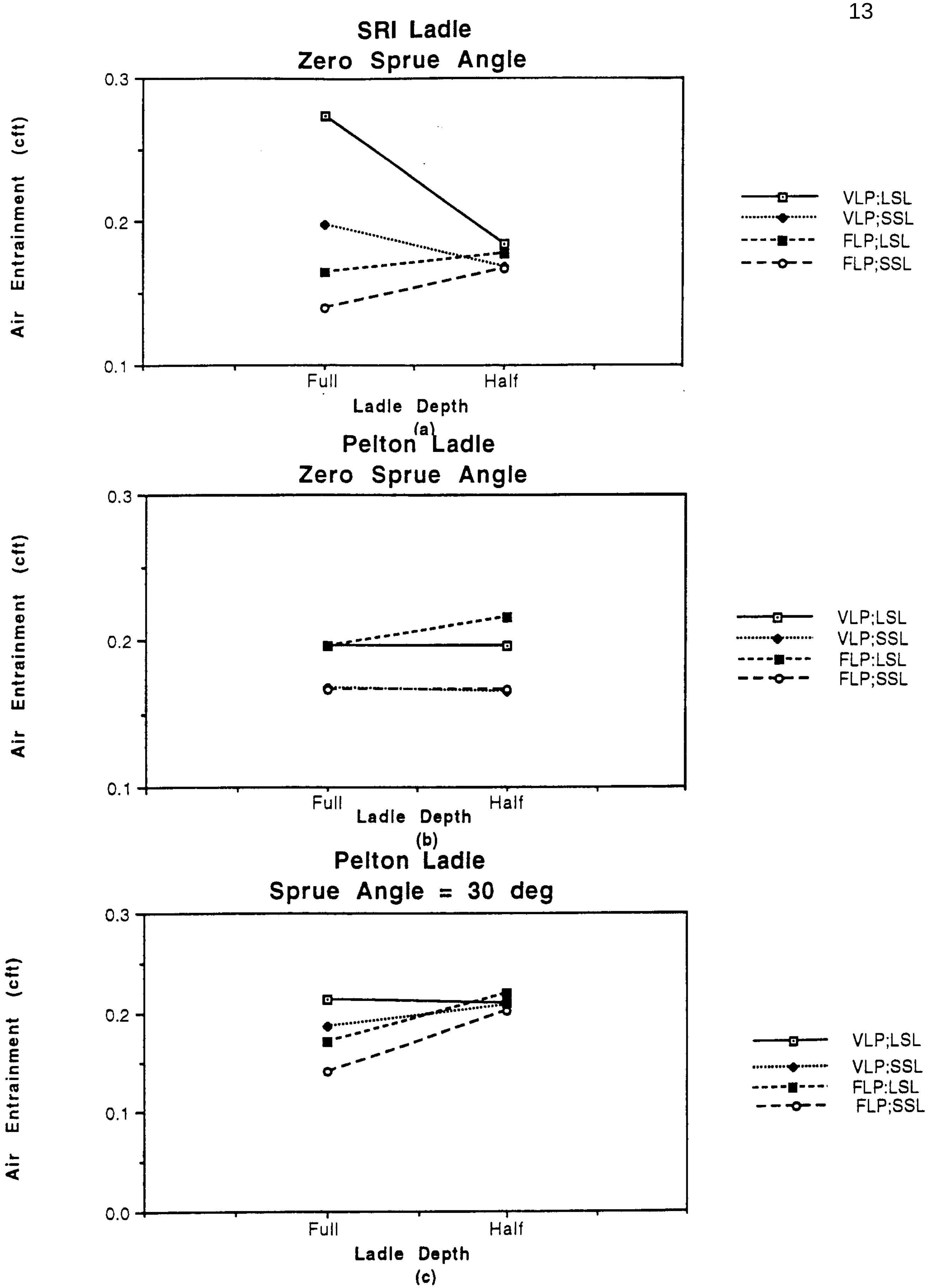


Figure 4. Effect of ladle depth on air entrainment.

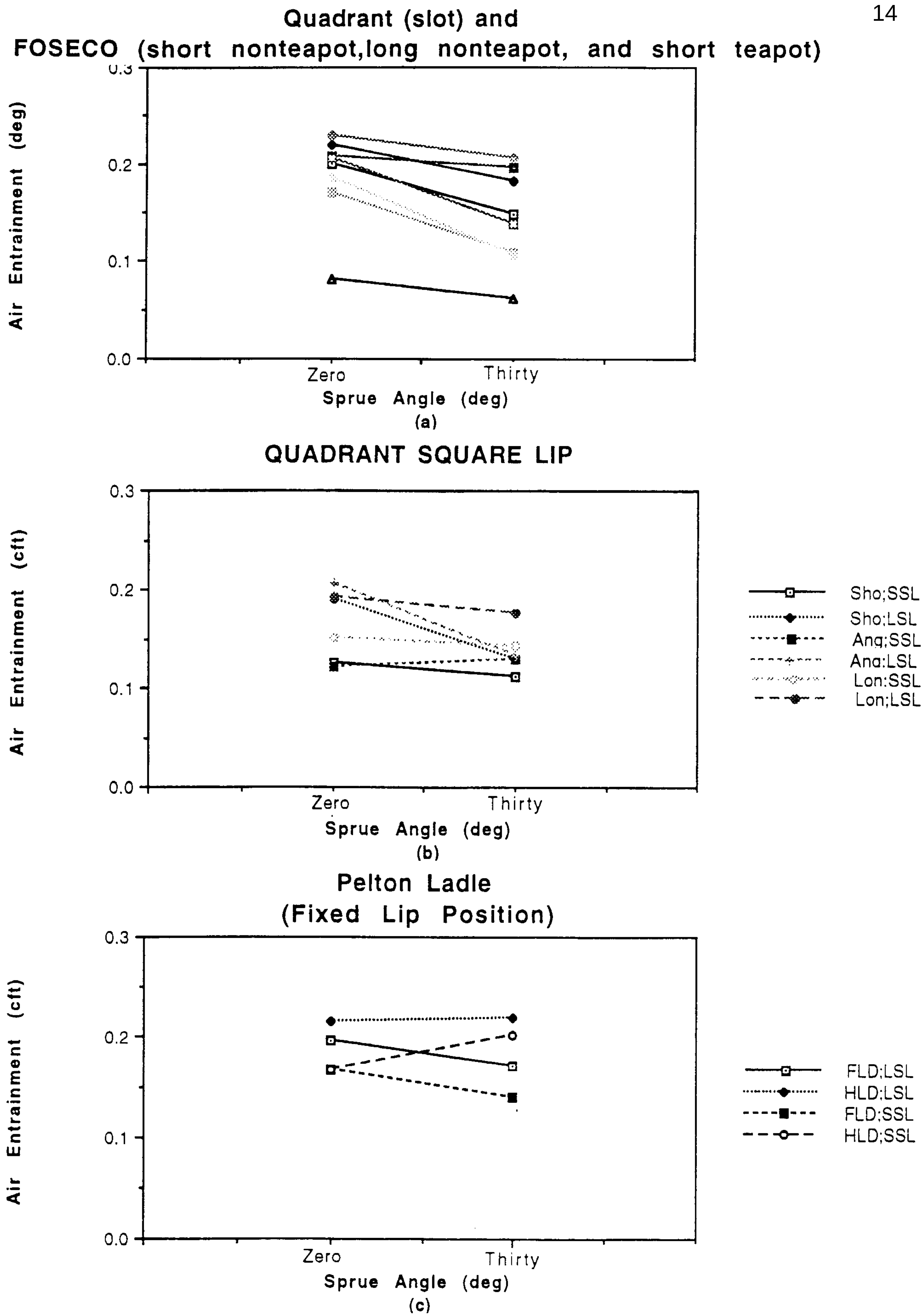
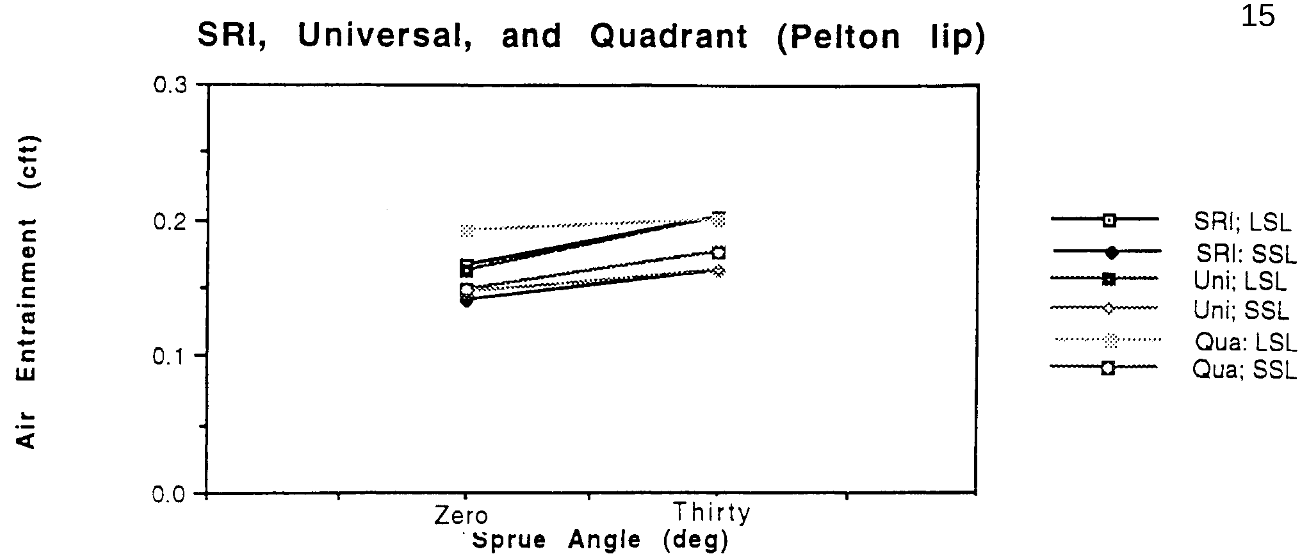
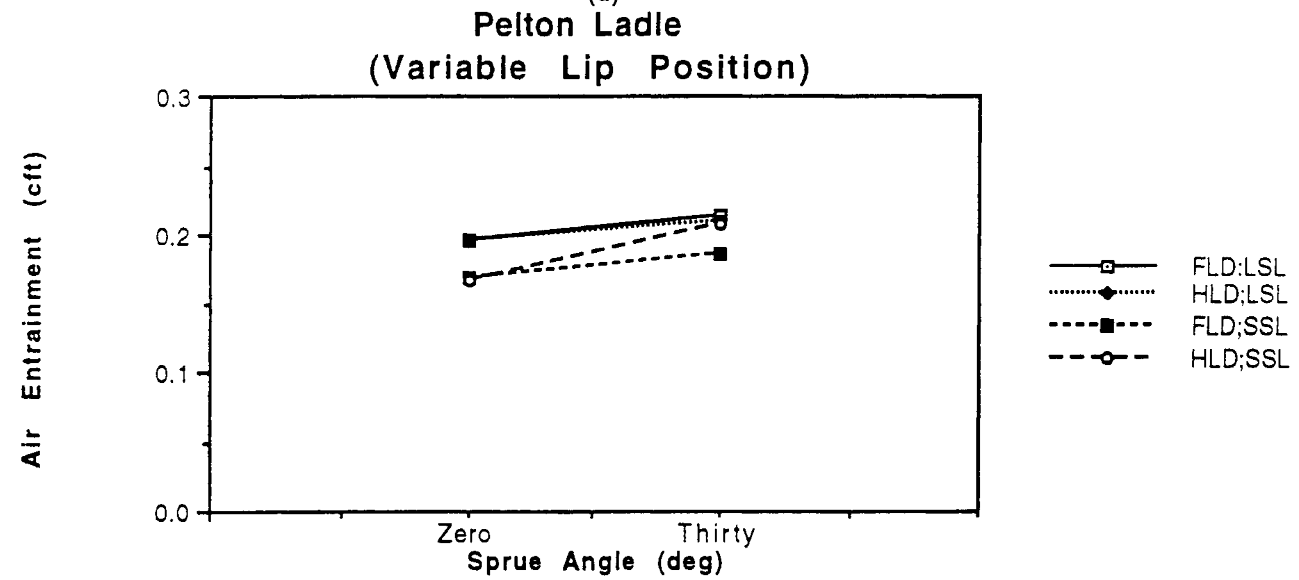


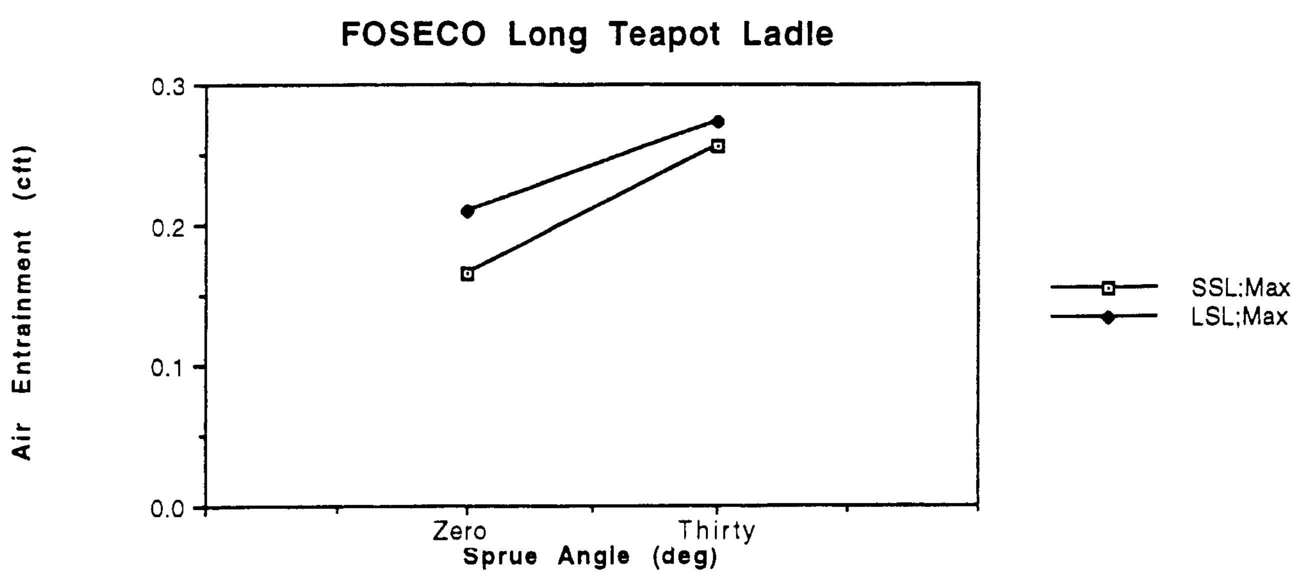
Figure 5. Effect of sprue angle on air entrainment.



(d)



(e)



(f)

Figure 5 (Continued). Effect of sprue angle on air entrainment.

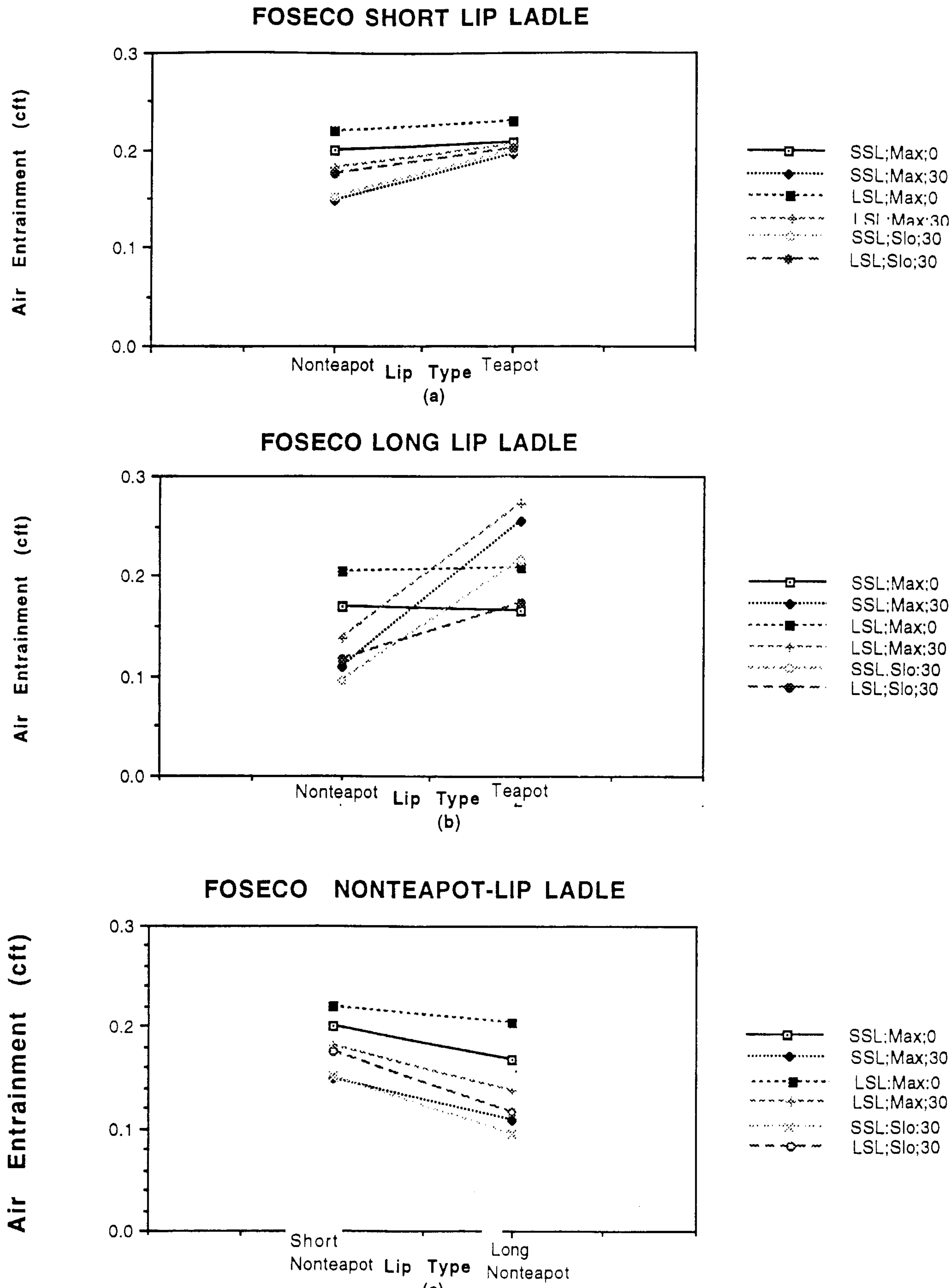


Figure 6. Effect of lip shape on air entrainment.

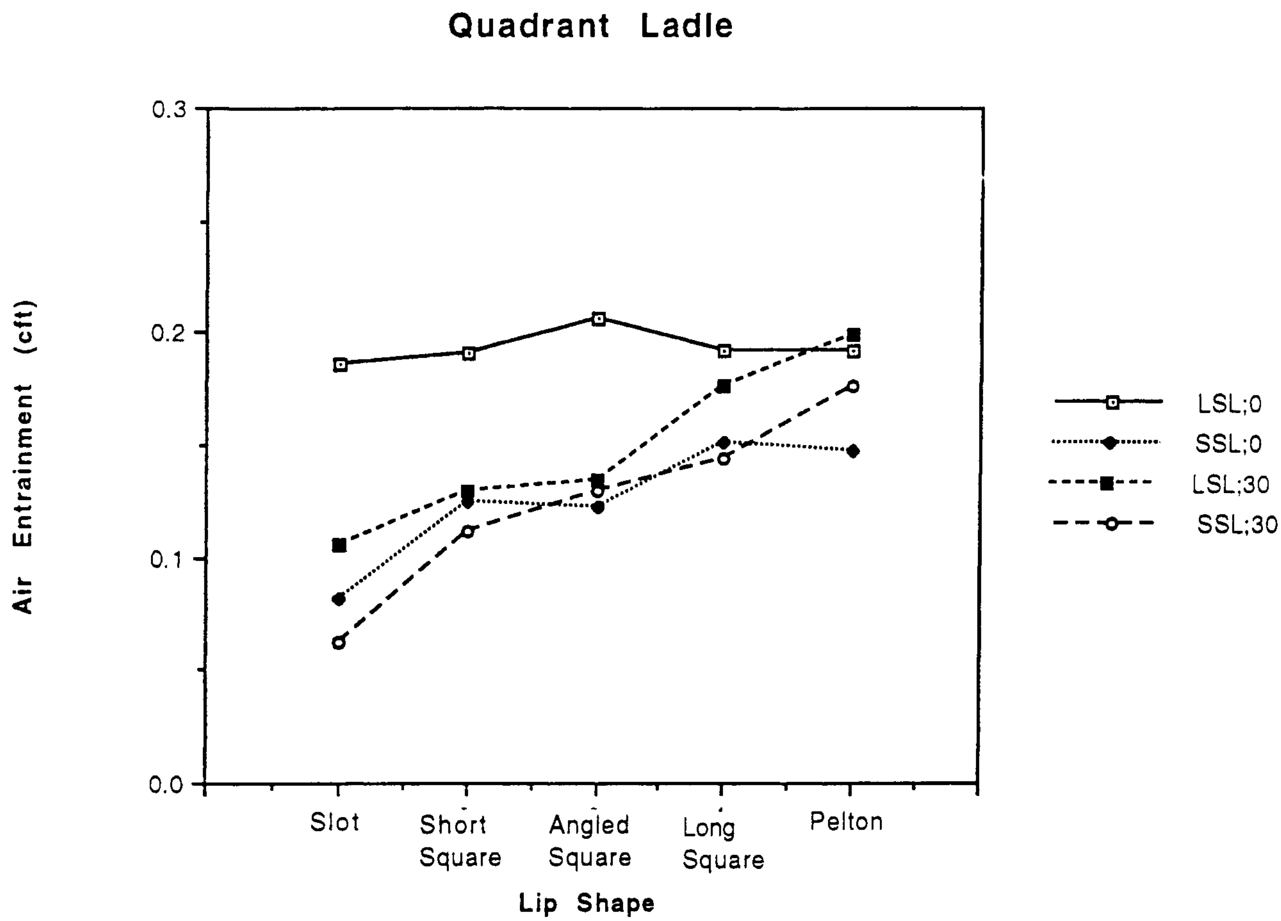


Figure 7. Effect on air entrainment of lip shape of the Quadrant ladle.

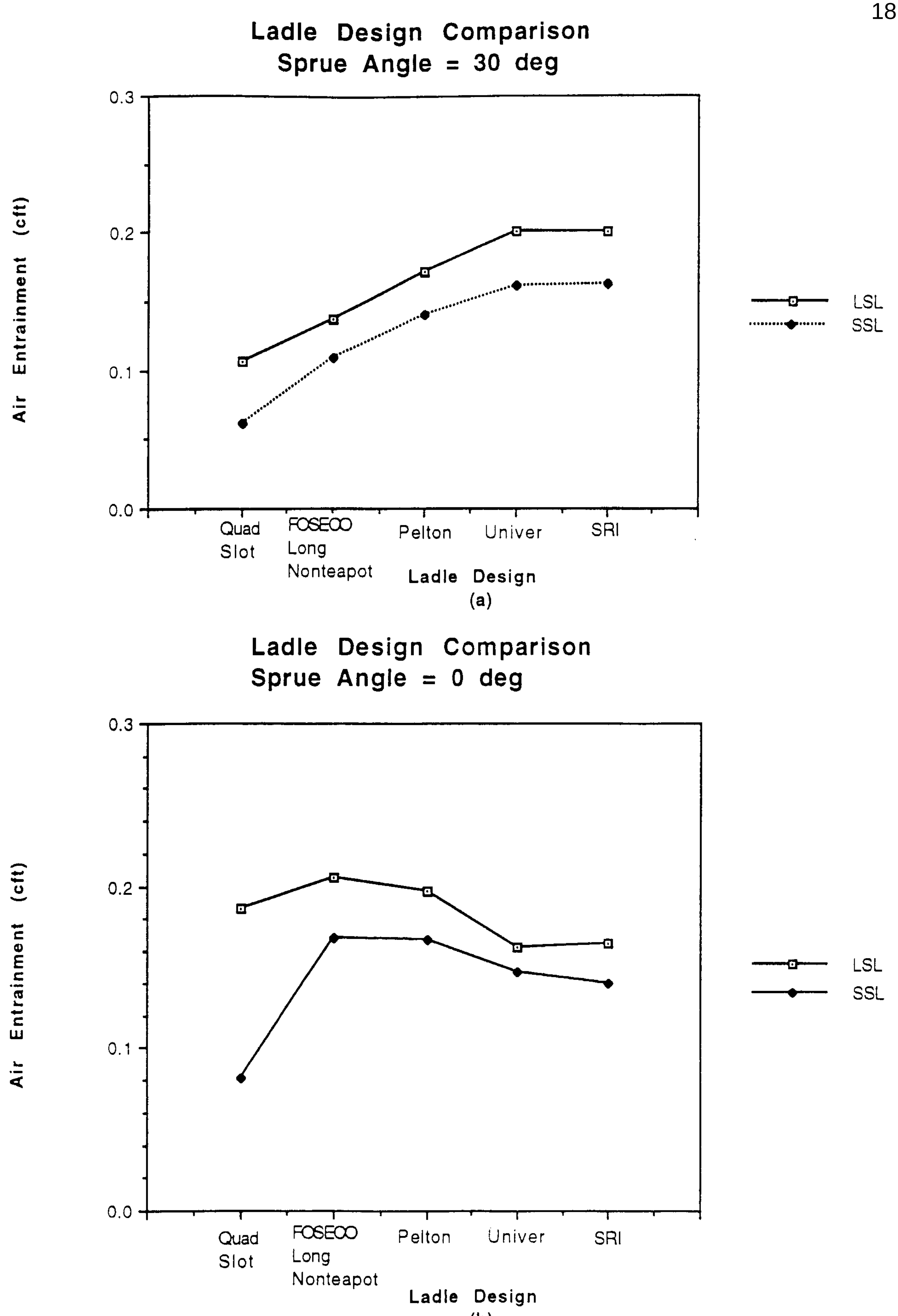


Figure 8. Effect of ladle design on air entrainment.