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CARBIDE AND CARBON CHEMICALS DIVISION
Union Carbide and Carbon Corporation

MEMORANDUM

EPS-K113

K-5001

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AECU-3241

September 30, 1950

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FROM: Roarty, J. D. (Leader), Aykanian, A. A., and Lea, D. C.
SUBJECT: Pressure Drop in Tees

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I. INTRODUCTION

Pressure drops of fluids for various flow configurations in pipe tees are important for plant design considerations. Reliable data on the pressure drops through the different branches in tees have not been obtained in the past for all possible configurations. In this investigation, an attempt was made to formulate an experimental basis for predicting such pressure drops within the limits justified by the equipment. The flow configurations possible are shown in Fig. 1, with the corresponding identification to which reference will be made throughout this memorandum.

The equipment used for the analysis of pressure drops consisted primarily of a 3/4-in. copper tubing system. The fluid used was water.

The specific information sought in this experiment was: (1) an analysis and possible correlation of the data for pressure drops in the various configurations, and (2) a determination of the resistance coefficients (K's) for branch flows.

The work performed on this experiment was carried out between September 13 and September 30, 1950.

II. RESULTS

The results of this investigation are presented as follows:

1. Pressure drops vs. incoming stream mass flows are presented for the four configurations in Figs. 2 through 9.
2. Resistance coefficients, K's, are plotted against the ratios of branch flows in Figs. 10 through 13.
3. The mathematical expressions developed to identify the pressure drop for various flows are tabulated below.

Configuration A _{ab}	$\Delta P = 0.008 W_a^{1.73}$
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Configuration A _{ac}	$\Delta P = 0.0035(W_a/W_c) W_a^{1.35} - 0.30$
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Configuration B _{ac}	$\Delta P = 0.002(W_a/W_c)^{-1} W_a^2$
-------------------------------	--

Configuration C _{ba}	$\Delta P = (0.003 + 30W_b/W_a) W_b^2$
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CONFIGURATION A

CONFIGURATION B

CONFIGURATION C

CONFIGURATION D

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FLOW CONFIGURATIONS

DATE 9/30/50	DRAWN BY D.C.L.	FILE NO. EPS-K113	FIG. 1
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$$\begin{aligned} \text{Configuration } C_{bc} \quad \Delta P &= \left[0.0046 - (w_b/w_c - 1)^{-1.7} \right] w_b^2 \\ \text{Configuration } D_{ab} \quad \Delta P &= 0.001(w_a/w_b)^{-1} w_a^{2.7} \\ \text{Configuration } D_{cb} \quad \Delta P &= 0.0015(w_c/w_b)^{-2} w_c^2 \end{aligned}$$

III. DISCUSSION OF RESULTS

Pressure Drops

The curves presented in Figs. 2 through 9 indicate the actual pressure drops through the branches of a 3/4-in. copper tee for various configurations of flow. The graphs are plots of pressure drops due to the tee alone versus incoming flow rates for various flow ratios through the branches over which the pressure drop was measured. The pressure drop due to the tee is defined as the net change in pressure over a branch after correcting for velocity changes and for friction drop in the length of pipe between the pressure taps and the tee. The pressure drops discussed throughout this report are the drops which would be measured across the outlets of a standard tee. These pressure drops are slightly greater than the permanent pressure drops which would occur if sufficient piping were connected to the exit branches to allow recovery of energy from transfer of momentum and decay of vorticity after the fluid leaves the tee.

Curves of pressure drop versus flow rate for configuration A_{ab} are presented in Fig. 2. The empirical equation reported for this configuration is the equation of the best line through all the data and does not take into account the slight effect of flow ratio on pressure drop for this configuration. The considerable scatter of data points at low rates for all configurations is due largely to fluctuation in flow rates. This is more evident in the plot of resistance coefficients, Fig. 10.

No simple mathematical expression could be developed for configuration B_{bc}. The large scatter of the data for this configuration is thought to be due to inaccuracies in setting flow ratios.

Resistance Coefficients

The plots of resistance coefficient, K, versus flow ratios (Figs. 10-13) are derived from the results shown in Figs. 2 through 9 and present the data in a form frequently used in piping design. The resistance coefficient is defined as $2g_c \Delta P / \rho V^2$, the ratio of the pressure drop due to the tee alone to the inlet velocity head. The plot of resistance coefficients for configuration A is similar to a plot reported by Freeman (2) who measured pressure drops for the same flow configuration in large size

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CONFIGURATION - A_{ab}

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CONFIGURATION - A_{ao}

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PRESSURE DROPS AT VARYING
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CONFIGURATION - B_{ac}

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CONFIGURATION - B_{bc}

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DATE 9/29/50 J.D.R. FILE NO. EPS-K113 FIG. 5

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CONFIGURATION - C_{ba}

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CONFIGURATION - C_{bo}

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CONFIGURATION - D_{ab}

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PRESSURE DROPS AT VARYING
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CONFIGURATION - D_{ob}

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PRESSURE DROPS AT VARYING
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CONFIGURATION - A

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RESISTANCE COEFFICIENTS

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FIG
10

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CONFIGURATION - B

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RESISTANCE COEFFICIENTS

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CONFIGURATION - C

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FIG.
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CONFIGURATION -D

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FIG.
13

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tees. This leads to the tentative conclusion that the resistance coefficients obtained in this investigation may be extrapolated to larger pipe sizes.

The results of this work differ appreciably from pressure drops and resistance coefficients obtained from a correlation presented by Vazsonyi (6). However, since the constants in Vazsonyi's correlation were obtained from a few data taken under widely varying conditions, this correlation can be expected only to give orders of magnitude of pressure drops over a wide range of flow conditions. The results of the present investigation are thought to give more accurate values of pressure drops in the relative narrow limits of flow rates and flow ratios adhered to.

In this work the Reynolds number of the approach stream in the case of diverging flow and of the exit stream in the case of converging flow varied from 24,300 to 72,300. Within this range the Reynolds number was found to have little effect upon the resistance coefficients.

Negative Pressure Drops

In some configurations of diverging flow, negative pressure drops were obtained in the region of low flow rates (cf. Figs. 3 and 10). Negative pressure drops over a single branch of diverging flow have also been observed by other investigators (2). Such negative pressure drops always occurred for the undiverging (or "straight-through") stream and indicate a net pressure rise from the source to the terminal of the branch after pressure changes due to deceleration and friction have been taken into account. Clearly, such a pressure increase can result only from a transfer of energy from the diverging to the undiverging stream. There must always be a net energy loss for the entire system, however, and this was substantiated in every case by writing a total energy balance around the three terminals of the tee.

Negative pressure drops were also observed for configuration B_{bc} at low flow rates of the side stream, W_b . This phenomenon is similar to that reported by Hoopes, Isakoff, Clarke, and Drew (4) who studied characteristics of flow through a commercial cast iron screwed tee.

The flow pattern of a stream through a tee is difficult to define by some stream function as treated in the case of non-branching flow through simple geometrical shapes. An approach to analyzing the characteristics of diverging flow through a tee is to assume the incoming stream is divided into two effluent streams by an imaginary layer, across which no mass or energy is transferred. In such a case each stream would act as if the other stream were not present. This assumption obviously does not hold for the cases in which a net energy increase (or negative pressure drop) was observed for the undiverted stream. This energy increase is explained by the hypothesis that vortices are shed from one stream to the other in the region in which the streams diverge. The effect of the vortices is to transmit energy from the faster moving stream going through the right angle bend to the slower moving stream passing undiverted through the tee. This is reasonable since, during the diverging process, elements of the diverging

stream possess momentum vectors in the direction of the undiverging stream. This phenomenon is more noticeable at low flow rates where the effect of the pipe friction loss in the tee is relatively small and the energy transferred by the vortices becomes important. Photographs of the flow characteristics in the diverging region of the glass tee, taken by Giesecke and Badgett (3), indicate considerable eddying in this region and further substantiate this theory.

The negative pressure drops observed for converging flow in configuration B_{bc} must be due to some different mechanism. In the case of low flow rates of stream C relative to the flow rates of stream B, the vector of momentum resulting from a collision of an element of fluid B with an element of fluid C must be essentially in the direction of the exit stream. This is the condition under which aspirators and jet ejectors produce the greatest pressure change from the side stream to the mixed stream. Hence, the pressure rise noted in this configuration may be explained merely as due to an aspirator effect, or the directional transfer of momentum from elements of stream B to elements of stream C.

IV. CONCLUSIONS

1. The effect of flow ratios on pressure drops follows a definite trend in most configurations with the exception of A_{ab} where no trend could be deduced.
2. The equation expressing pressure drop as a function of incoming mass flow indicates that the velocity term could have a greater or lesser effect on the pressure drop than that expected for straight pipe.
3. Negative pressure drops are possible in certain flow configurations.
4. Extrapolation of these data to larger pipe sizes is considered feasible.
5. The resistance coefficients indicated lower values than could be determined from the sketchy information available in the literature (1).
6. No general correlation between configurations was apparent.

V. RECOMMENDATIONS

1. Further investigation should be carried out to determine pressure losses in tees as affected by size and shape of the tees and characteristics of the fluids.
2. A system of greater flow capacity should be built to allow the study of larger tees.
3. Operating conditions of the present system could be improved by installing a 1-hp. motor to replace the 3/4-hp. motor used in this work.

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VI. PROCEDURE

Design and Construction of Apparatus

The apparatus was designed to obtain every possible flow configuration through the test tee (see Fig. 1). The test section consisted of a 3/4-in. o.d. copper tubing tee with three calming sections each 37-1/2-in. long. These sections are equivalent to about fifty diameters. The remainder of the network consisted of 3/4-in. copper tubing with globe valves to regulate the desired flow quantities. A 55-gal drum was used as a reservoir, and the water was recycled.

A 15-gpm Rotary Pump was included in the system as it was felt that tap pressure would introduce variations in flow conditions.

The flow was measured by two Fisher and Porter Rotameters inserted in two branches of the tee. The flow through the third branch of the tee was obtained by difference.

Pressure tap points in the calming sections were located about 6 and 22 diameters from the test tee. Piezometer rings were constructed and placed over four static holes drilled at an angular spacing of 90° as shown in Fig. 14.

The instrumentation for pressure measurements consisted of two differential manometers. The desired sensitivity was achieved by using a manometer fluid of specific gravity 2.95 in one and carbon tetrachloride colored by iodine, specific gravity 1.577, in the other. A bourdon-type pressure gage was installed in the outlet of the pump to indicate the operating pump pressure.

The test equipment was constructed in the MIT Practice School, Building K-1008C.

Operating Procedure

Four different configurations of flow in one tee size were tested. For each configuration pressure drops across the inlet and outlet branches of the tee were taken, and pressure drops in each calming section were recorded.

To avoid an elaborate switching network for the manometer connections, the flow ratios were varied over the full range for one setting of the pressure taps. Then the taps were changed, and the procedure was repeated.

To obtain the various flow configurations, the water was properly routed through the system by adjusting the position of globe valves.

Calculation Procedure

The method of evaluating the actual pressure losses in the tee was to

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PRESSURE DROP TEST APPARATUS

DATE	DRAWN BY	FILE NO.	FIG.
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evaluate the difference between the total pressure drop between manometer taps and the sum of the individual drops which could be charged as the loss in an equivalent length of straight pipe and to the loss due to the change in velocity.

Two piezometer rings separated by approximately 16 diameters were used to evaluate the actual drop in the tubing between the piezometer ring and the tee itself. A linear relationship between the drop measured in the calming section and the distance between the rings was assumed which permitted an extrapolation of this tubing loss to the face of the test tee (5).

The change in velocity head between any two branches under test was calculated by taking an energy balance between the two branches.

Location of Original Data

The original data of this investigation are located in Notebook No. 1563, pp. 2-17, inclusive.

VII. APPENDIX

Nomenclature

D	Inside diameter, = 0.652 in.
g_c	Constant, = 32.2 (ft)(lb matter)/(sec)(sec)(lb force)
H	Manometer reading, in.
h_l	Energy loss, (ft)(lb force)/lb matter
K	Resistance coefficient, dimensionless
m	Mass, lb mass
V	Velocity, fps
W	Flow rate, gpm
ρ	Density, = 62.4 lb/cu ft
ΔP	Pressure difference, lb/sq ft

Subscripts

a,b,c	Tee branches or leg. (see Fig. 1)
m	Manometer
p	Pipe
T	Tee
v	Velocity head

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Sample Calculations

Data Recorded:

Two flow rates (a and b) in gpm.

Two pressure drops across tee at distance of approximately 6 D in each branch.

Three pressure drops in calming section between piezometer rings (See Fig. 14).

General Equation for Pressure Drop in Tee:

$$\Delta P_T = \Delta P_m - \Delta P_v - \Delta P_p \quad (1)$$

(All terms were calculated in lb/(ft)(ft))

$$\underline{\Delta P_m}$$

$$\Delta P_m = \frac{H}{12} (\rho_{\text{Man. Fluid}} - \rho_{\text{Water}}) \quad (2)$$

$$\text{Manometer 1} \quad \Delta P_m = \frac{H}{12} (2.95 - 1.00)(62.4) = 10.14 H \quad (3)$$

$$\text{Manometer 2} \quad \Delta P_m = \frac{H}{12} (1.577 - 1.00)(62.4) = 3.00 H \quad (4)$$

$$\underline{\Delta P_v}$$

$$V = \frac{4 W}{\pi D^2} \quad (5)$$

$$V = \frac{W (8.34)(144)(4)}{(60)(62.4)(0.652)^2 \pi} = 0.962 W \quad (6)$$

$$\Delta P_v = \frac{(V_b^2 - V_a^2)}{2 g_c} = \frac{(0.962)^2 (62.4) (W_b^2 - W_a^2)}{64.4} = 0.896 (W_b^2 - W_a^2) \quad (7)$$

$$\underline{\Delta P_p}$$

Piezometers were 4-1/8 in. from end of pipe

Piezometers were 14-3/8 in. from end of pipe

$$\Delta P_p = \frac{4.125}{10.25} (\Delta P_{mp}) = 0.402 \Delta P_{mp} \quad (8)$$

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$$\Delta P_p = 1.206 H \text{ on No. 2 manometer, } 4.075 H \text{ on No. 1 manometer} \quad (9)$$

Substituting eq. (3), (4), (7), (9), into (1):

$$\Delta P_T = \left. \begin{array}{l} 10.14 H_{m1} \\ 3.00 H_{m2} \end{array} \right\} - 0.896 (W_2^2 - W_1^2) - \left\{ \begin{array}{l} 4.075 H_{mp1} \\ 1.206 H_{mp2} \end{array} \right. \quad (10)$$

Calculation of K (Branch ab)

$$\Delta P_T = \frac{KV_a^2}{2 g_c} \quad K = \frac{(2) (32.2) (\Delta P_T)}{(0.962)^2 (62.4) (W_a^2)} = \frac{1.115(\Delta P_T)}{W_a^2} \quad (11)$$

Sample, Configuration A, Run No. 17

$$\begin{aligned} W_a/W_b &= 1.33 \\ W_a &= 10.0 \text{ gallons} \\ H_{ab} &= 12.4 \text{ in. (No. 2)} \\ H_{pa} &= 9.3 \text{ in. (No. 2)} \\ H_{pb} &= 6.5 \text{ in. (No. 2)} \end{aligned}$$

$$\Delta P_m = 3.00 H_{m2} = (3.00) (12.4) = 37.2 \text{ psf} \quad (12)$$

$$\Delta P_v = 0.896 (W_b^2 - W_a^2) = 0.896 (7.5^2 - 10.0^2) = -39.2 \text{ psf} \quad (13)$$

$$\Delta P_p = 1.206 (H_{pa} + H_{pb}) = (1.206) (9.3 + 6.5) = 19.1 \text{ psf} \quad (14)$$

Substituting into eq. (10):

$$\Delta P_T = 37.2 - (-39.2) - 19.1 = 57.3 = \frac{57.3}{144} \text{ psi} = 0.40 \text{ psi} \quad (15)$$

Substituting into eq. (11):

$$K = \frac{(1.115) (57.3)}{(10.0)^2} = 0.640 \quad (16)$$

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Calculation of Energy Losses:

Configuration C

From the General Energy Equation:

$$W_b \left(\frac{V_b^2}{2g_c} + \frac{P_b}{\rho} \right) = W_a \left(\frac{V_a^2}{2g_c} + \frac{P_a}{\rho} \right) + W_c \left(\frac{V_c^2}{2g_c} + \frac{P_c}{\rho} \right) + W_b h_1 \quad (17)$$

$$W_c = W_b - W_a \quad V_c = V_b - V_a \quad (18)$$

Solving eq. (17) for h_1 :

$$h_1 = \frac{\Delta P_{mbc}}{\rho} + \frac{W_a}{W_b} \frac{\Delta P_{mca}}{\rho} - \frac{V_a}{2g_c} (2V_b - V_a) + \frac{W_a}{W_b} \frac{V_b}{2g_c} (V_b - 2V_a) \quad (19)$$

$$V = 0.962 W$$

$$h_1 = \frac{\Delta P_{mbc}}{\rho} + \frac{W_a}{W_b} \frac{\Delta P_{mca}}{\rho} + \frac{(0.962)^2}{2g_c} W_a (2W_b - W_a) + \frac{(0.962)^2 W_a W_b}{2g_c W_b} (W_b - 2W_a) \quad (20)$$

$$h_1 = \frac{1}{\rho} (\Delta P_{mbc} + \frac{W_a}{W_b} \Delta P_{mca}) + \frac{(0.962)^2}{2g_c} (3W_a W_b - 3W_a^2) \quad (21)$$

$$h_1 = 0.016 (\Delta P_{mbc} + \frac{W_a}{W_b} \Delta P_{mca}) + 0.0432 W_a (W_b - W_a) \quad (22)$$

$$h_T = h_1 - h_p \quad (23)$$

Sample, Runs Nos. 87 and 107 (which accounts for both run and branch of Configuration C)

$$\Delta P_{mba} = -49.0$$

$$\Delta P_{mbc} = 90.6$$

$$W_a = 3.0 \text{ gallons}$$

$$W_b = 15.0 \text{ gallons}$$

$$\Delta P_{pa} = 5.1$$

$$\Delta P_{pb} = 77.1$$

$$\Delta P_{pc} = 42.0$$

$$\Delta P_{ba} = \Delta P_{mba} - (\Delta P_{pb} + \Delta P_{pa}) \frac{4.125}{10.25} \quad (24)$$

$$\Delta P_{ba} = -49.0 - (77.1 + 5.1) \frac{4.125}{10.25} = -82.1 \quad (25)$$

$$\Delta P_{bc} = 90.6 - (77.1 + 42.0) \frac{4.125}{10.25} = 42.6 \quad (26)$$

$$\Delta P_{ca} = \Delta P_{ba} - \Delta P_{bc} = -124.7 \quad (27)$$

Using eqs. (22) and (23) and substituting from eqs. (26) and (27)

$$h_T = .016 \left[42.6 + 1/5 (-124.7) \right] + 0.0432 \times 3 (15-3) = 1.84 \quad (28)$$

ft lb/lb.

Summary of Data

Configuration Aab (Fig. 2)

Run No.	Ratio W_a/W_b	W_a	W_b	H_{ab1}	H_{ab2}	H_{a2}	H_{b2}	ΔP_T	K_{ab}
7	1.00	14.2	14.2	20.4		18.7	26.0	1.06	0.852
8		12.0	12.0	14.0		13.6	20.8	0.61	0.686
15		10.0	10.0	10.0		8.9	14.8	0.51	0.812
24		5.0	5.0		9.3	2.9	4.5	0.13	0.849
6	1.25	14.5	11.6	8.9		18.9	16.7	0.80	0.613
9		12.0	9.6	6.3		13.5	13.5	0.54	0.603
16		10.0	8.0		3.5	8.5	6.0	0.18	0.288
25		5.0	4.0		5.8	2.9	1.8	0.14	0.862
10	1.33	12.0	9.0		16.6	13.5	10.6	0.54	0.598
1		15.0	11.3	8.4		19.2	17.1	0.90	0.645
17		10.0	7.5		12.4	9.3	6.5	0.40	0.639
26		5.0	3.75		5.0	2.9	2.9	0.12	0.796
2	1.50	15.0	10.0		14.4	20.5	12.2	0.80	0.577
11		12.0	8.0		11.4	13.7	8.3	0.55	0.617
18		10.0	6.67		8.7	9.4	5.3	0.40	0.649
21		9.0	6.0		6.8	7.7	3.9	0.33	0.646
23		6.0	4.0		4.5	4.0	1.9	0.17	0.755
27		5.0	3.33		3.4	2.6	1.2	0.13	0.810
3	2.00	15.0	7.5		3.7	21.8	6.0	0.90	0.641
12		12.0	6.0		2.2	13.6	4.3	0.57	0.635
19		10.0	5.0		2.6	9.5	2.9	0.42	0.671
4	3.00	15.0	5.0		-3.9	21.8	1.9	0.97	0.693
13		12.0	4.0		-1.6	13.8	2.5	0.63	0.701
20		10.0	3.33		-0.1	9.7	0.6	0.47	0.747
22		9.0	3.0		-0.5	7.8	0.0	0.37	0.741
5	4.00	15.0	3.75		-5.6	21.8	0.6	1.00	0.724
14		12.0	3.0		-3.0	16.1	0.4	0.64	0.716

Notes: H_{ab1} refers to reading on Manometer 1 in inches of manometer fluid.
 H_{ab2} , H_{a2} , H_{b2} , refer to readings on Manometer 2 in inches of manometer fluid.

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Configuration A_{ac} (Fig. 3)

Run No.	Ratio W_a/W_c	W_a	W_c	H_{ac1}	H_{ac2}	H_{a2}	H_{c2}	ΔP_T	K_{ac}
28	1.33	15.0	11.3	-12.3		21.8	1.6	-0.45	-0.322
34		12.0	9.0	-5.6		16.1	8.9	-0.21	-0.237
29	1.50	15.0	10.0	-9.0		21.8	7.4	-0.10	-0.072
35		12.0	8.0	-7.4		13.8	6.7	-0.19	-0.217
39		10.0	6.67	-6.1		9.7	4.5	-0.20	-0.322
44		9.0	6.0	-5.5		7.8	3.7	-0.20	-0.405
30	2.00	15.0	7.5	-11.2		21.8	7.2	+0.01	0.010
36		12.0	6.0	-8.6		13.6	5.1	-0.09	-0.099
40		10.0	5.0	-6.6		9.5	2.9	-0.10	-0.164
31	3.00	15.0	5.0	-12.2		20.5	6.9	0.16	0.110
41		10.0	3.33	-6.7		9.4	2.6	-0.02	-0.031
45		9.0	3.0	-6.1		7.7	1.4	-0.06	-0.121
46		6.0	2.0	-4.8		4.0	1.1	-0.18	-0.810
47		5.0	1.67	-4.5		2.6	1.3	-0.21	-1.36
32	4.00	15.0	3.7	-12.3		19.2	1.6	0.27	0.196
37		12.0	3.0	-9.6		13.5	2.0	0.03	0.038
42		10.0	2.5	-6.7		9.3	2.4	0.01	0.022
48		5.0	1.33	-4.3		2.9	1.0	-0.19	-1.22
33	5.00	14.5	2.9	-11.4		18.9	2.4	0.28	0.213
38		12.0	2.4	-8.9		13.5	2.0	0.10	0.116
43		10.0	2.0	-6.5		8.5	1.5	0.06	0.089
49		5.0	1.0	-4.3		2.9	0.8	-0.18	-1.09

Notes:

H_{ac1} refers to reading on Manometer No. 1 in inches of manometer fluid.

H_{ac2} , H_{a2} , etc., refer to readings on Manometer No. 2 in inches of manometer fluid.

Configuration B_{ac} (Fig. 4)

Run No.	Ratio W_a/W_c	W_a	W_c	H_{ac1}	H_{ac2}	H_{a2}	H_{c2}	ΔP_T	K_{ac}
50	0.75	10.5	14.0	16.3		10.4	21.4	0.35	0.505
52		9.0	12.0	11.3		7.8	14.6	0.22	0.436
51	0.67	10.0	15.0	19.5		9.0	23.6	0.32	0.520
53		8.0	12.0	12.9		5.5	15.9	0.23	0.586
56		6.0	9.0	6.8		4.2	8.7	0.09	0.407
54	0.50	7.5	15.0	21.0		5.6	23.4	0.20	0.535
55		6.0	12.0	15.0		3.9	15.8	0.22	0.975
58		5.0	10.0	10.2		2.1	12.0	0.13	0.841
61		3.0	6.0	3.5		1.3	3.6	0.03	0.609
57	0.33	5.0	15.0	22.3		2.6	24.3	0.10	0.645
59		4.0	12.0	14.0		1.5	16.5	0.04	0.391
63		2.5	7.5	6.1		0.2	6.3	0.07	1.68
60	0.20	3.0	15.0	22.8		1.0	24.2	0.05	0.883
62		2.5	12.5	15.4		0.7	17.0	0.00	0.054
64		2.2	11.0	12.0		0.2	14.6	0.00	0.023
65		2.0	10.0	10.0		0.6	10.9	0.01	0.587
66		1.5	7.5	6.0		0.2	6.0	0.04	2.53

Configuration B_{bc} (Fig. 5)

Run No.	Ratio W_b/W_c	W_b	W_c	H_{bc1}	H_{bc2}	H_{b2}	H_{c2}	ΔP_T	K_{bc}
67	0.80	12.0	15.0	19.4		15.5	24.2	0.53	0.594
69		10.0	12.5	13.3		10.9	17.0	0.35	0.569
70		8.8	11.0	10.6		8.3	14.6	0.28	0.580
72		8.0	10.0	8.5		7.4	10.9	0.22	0.554
75		6.0	7.5	5.1		4.7	6.0	0.15	0.650
68	0.67	10.0	15.0	20.2		11.4	24.3	0.35	0.556
71		8.0	12.0	13.0		6.1	16.5	0.23	0.578
78		5.0	7.5	5.4		3.6	6.3	0.11	0.676

(Continued)

Notes:

H_{bc1} refers to reading on Manometer 1 in inches of manometer fluid.
 H_{bc2} , H_{b2} , etc., refer to readings on Manometer 2 in inches of manometer fluid.

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Configuration B_{bc} (Continued)

Run No.	Ratio W_b/W_c	W_b	W_c	H_{bc1}	H_{bc2}	H_{b2}	H_{c2}	ΔP_T	K_{bc}
73	0.50	7.5	15.0	19.4		6.0	23.4	0.07	0.205
74		6.0	12.0	13.5		4.4	15.8	0.11	0.491
77		5.0	10.0	9.6		3.9	12.0	0.07	0.475
83		3.0	6.0	3.7		2.6	3.6	0.04	0.783
76	0.33	5.0	15.0	19.2		3.0	23.6	-0.11	-0.730
79		4.0	12.0	13.0		2.0	15.9	-0.03	-0.300
82		3.0	9.0	7.0		1.8	8.7	-0.04	-0.770
80	0.25	3.5	14.0	16.2		2.2	21.4	-0.20	-2.90
81		3.0	12.0	11.9		1.8	14.6	-0.10	-2.46

Configuration C_{ba} (Fig. 6)

Run No.	Ratio W_b/W_a	W_b	W_a	H_{ba1}	H_{ba2}	H_{b2}	H_{a2}	ΔP_T	K_{ba}
90	1.00	12.6	12.6	17.1		4.0 ₁	6.0	0.92	0.932
91		12.0	12.0	15.1		4.9 ₁	19.4	0.76	0.852
95		10.0	10.0	10.5		3.3 ₁	13.5	0.54	0.863
105		5.0	5.0		9.8	2.8 ₂	3.8	0.15	0.958
84	2.00	15.0	7.5		8.0	7.7 ₁	7.0	0.95	0.679
92		12.0	6.0	2.2		4.1 ₁	4.8	0.67	0.748
96		10.0	5.0		4.9	3.1 ₁	3.4	0.45	0.725
101		8.0	4.0		3.2	5.9 ₂	2.2	0.30	0.750
103		6.0	3.0		2.0	4.7 ₂	1.4	0.16	0.708
106		4.0	2.0		1.0	2.3 ₂	0.8	0.07	0.706
85	3.00	15.0	5.0		-5.0	7.6 ₁	3.7	0.89	0.640
93		12.0	4.0		-2.5	4.4 ₁	2.5	0.60	0.670
97		10.0	3.33		-1.5	3.2 ₁	1.7	0.42	0.670
100		9.0	3.0		-1.0	8.6 ₂	1.3	0.34	0.685
104		6.0	2.0		0.0	3.9 ₂	0.9	0.16	0.711

(Continued)

Notes:

H_{bc1} refers to reading on Manometer 1 in inches of manometer fluid.

H_{bc2} , H_{b2} , etc., refer to readings on Manometer 2 in inches of manometer fluid.

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Configuration Cba (Continued)

Run No.	Ratio W_b/W_a	W_b	W_a	H_{ba1}	H_{ba2}	H_{b2}	H_{a2}	ΔP_T	K_{ba}
86	4.00	15.0	3.75	-3.8		7.6 ₁	2.2	0.81	0.580
88		14.0	3.5	-3.7		6.9 ₁	1.9	0.67	0.549
94		12.0	3.0		-9.1	4.4 ₁	1.5	0.51	0.575
98		10.0	2.5		-5.4	9.3 ₂	1.1	0.38	0.617
87	5.00	15.0	3.0	-4.8		7.6 ₁	1.7	0.77	0.555
89		13.0	2.6	-3.6		5.8 ₁	1.1	0.59	0.557
99		10.0	2.0		-7.0	9.9 ₂	0.8	0.36	0.581
102		7.5	1.5		-3.6	6.1 ₂	0.5	0.21	0.588

Configuration Cbc (Fig. 7)

Run No.	Ratio W_b/W_c	W_b	W_c	H_{bc1}	H_{bc2}	H_{c2}	H_{c2}	ΔP_T	K_{bc}
107	1.25	15.0	12.0	9.5		7.6 ₁	14.0	0.84	0.600
112		13.0	10.4	7.2		5.8 ₁	10.8	0.63	0.600
116		10.0	8.0		11.6	9.9 ₂	5.2	0.36	0.573
122		7.5	6.0		6.8	6.1 ₂	3.4	0.19	0.539
108	1.33	15.0	11.25	8.4		7.6 ₁	11.1	0.89	0.640
111		14.0	10.5	7.4		6.9 ₁	11.1	0.70	0.578
113		12.0	9.0	5.1		4.4 ₁	8.2	0.57	0.626
117		10.0	7.5		11.9	9.3 ₂	5.0	0.40	0.643
109	1.50	15.0	10.0		26.0	7.6 ₁	9.1	1.03	0.736
114		12.0	8.0	4.2		4.4 ₁	7.3	0.62	0.691
118		10.0	6.67		9.7	3.2 ₁	4.7	0.42	0.671
120		9.0	6.0		8.1	2.6 ₂	3.6	0.40	0.789
123		6.0	4.0		4.1	3.9 ₂	1.5	0.16	0.736
110	2.00	15.0	7.5		8.0	7.7 ₁	7.0	0.94	0.674
115		12.0	6.0	2.2		4.1 ₁	4.8	0.67	0.749
119		10.0	5.0		4.9	3.1 ₁	3.4	0.45	0.726
121		8.0	4.0		3.2	5.9 ₂	2.2	0.30	0.750
124		6.0	3.0		2.0	4.7 ₂	1.4	0.16	0.708
125		4.0	2.0		1.0	2.3 ₂	0.8	0.07	0.706

Notes: H_{bc1} refers to readings on Manometer 1 in inches of manometer fluid.
 H_{bc2} , etc. refers to readings on Manometer 2 in inches of manometer fluid.

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Configuration D_{ab} (Fig. 8)

Run No.	Ratio W_a/W_b	W_a	W_b	H_{ab1}	H_{ab2}	H_{a2}	H_{b2}	ΔP_T	K_{ab}
133	0.50	7.4	14.8	27.3		5.0	30.4	0.61	1.78
134		6.0	12.0	17.0		3.7	19.3	0.33	1.47
137		5.0	10.0	11.0		2.7	13.2	0.18	1.15
140		4.0	8.0	6.9		2.0	8.8	0.10	0.978
142		2.0	4.0	1.6		0.7	9.1	-0.05	-1.84
129	0.67	9.4	14.3	23.5		7.6	30.4	0.61	1.11
131		8.0	12.0	16.0		6.3	19.3	0.41	1.04
135		6.0	9.0	8.7		3.7	10.8	0.21	0.937
138		5.0	7.5	6.0		2.8	7.3	0.14	0.930
141		4.0	6.0	3.8		1.8	4.7	0.09	0.930
127	0.80	10.0	12.5	16.0		9.0	23.6	0.50	0.806
130		9.0	11.25	12.7		8.1	18.3	0.39	0.779
132		8.0	10.0	9.6		6.3	12.5	0.29	0.736
136		6.0	7.5	5.4		3.7	6.5	0.17	0.948
126	1.00	12.8	12.8	18.9		15.5	22.0	1.00	1.00
128		10.0	10.0	9.4		9.5	13.5	0.47	0.750
139		5.0	5.0	2.8		2.7	13.5	0.06	0.380
143		2.0	2.0	1.4		0.6	0.6	0.09	3.52

Configuration D_{cb} (Fig. 9)

Run No.	Ratio W_c/W_b	W_c	W_b	H_{cb1}	H_{cb2}	H_{b2}	H_{c2}	ΔP_T	K_{cb}
151	0.20	2.5	12.5	19.0		23.6	0.6	0.20	5.25
153		2.25	11.25	16.0		18.3	0.4	0.21	6.72
154		2.0	10.0	12.0		12.5	0.2	0.14	5.77
157		1.5	7.5	6.4		6.5	0.0	0.06	4.37
147	0.33	4.9	14.3	25.2		30.4	3.0	0.37	2.51
148		4.0	12.0	17.2		19.3	2.0	0.23	2.34
150		3.0	9.0	9.3		10.8	0.6	0.11	1.95
152		2.5	7.5	6.4		7.3	0.6	0.07	1.91
155		2.0	6.0	5.4		4.7	0.0	0.14	5.79

(Continued)

Notes:

H_{ab1} and H_{cb1} refer to readings on Manometer 1 in inches of manometer fluid.
 H_{ab2} , H_{cb2} , H_{a2} , H_{b2} , etc. refer to readings on Manometer 2 in inches of manometer fluid.

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Configuration Dcb (Continued)

Run No.	Ratio W_c/W_b	W_c	W_b	H_{cb1}	H_{cb2}	H_{b2}	H_{c2}	ΔP_T	K_{cb}
144	0.50	7.4	14.8	27.3		30.4	5.0	0.61	1.78
145		6.0	12.0	17.0		19.3	3.7	0.30	1.47
146		5.0	10.0	11.0		13.2	2.7	0.18	1.04
149		4.0	8.0	6.9		8.8	2.0	0.10	0.979
156		2.0	4.0	1.6		9.1	0.7	-0.05	-1.84

Error Analysis

The variation in flow rate as indicated by the flow meters was estimated to be ± 0.2 gpm at all rates about 3 gpm. At flow rates less than 3 gpm in line b or less than 2 in line a, the values are not reliable and may be off by as much as 25%. However, there are very few points in the data which have flow rates less than these values.

The various pressure drops in any one configuration were determined from repeated flow settings. One pressure drop for all flow conditions was obtained, the manometer leads were changed, and the same flow conditions were produced. The precision in duplicating the same conditions was about 5%, as determined by the precision of the flow meters.

The liquid level in the manometers fluctuated considerably at high flow rates, especially in No. 2 manometer. The maximum error in reading was 0.5 inches.

As the absolute value of the manometer reading diminished, so did the amount of fluctuation. At very low values, for example when determining the pressure drop across a length of straight pipe at a low flow rate, the fluctuation was a relatively large fraction of the total reading. However, this pressure loss due to pipe friction was in the cases (of converging flow) very small compared to the loss due to the change in velocity head between that low flow and a higher flow beyond the tee. Therefore, in such cases, the calculated net loss in the tee did not suffer greatly from a large percentage error in manometer reading. The maximum effect of this error on the final tee loss was 5%, based on precision in reading at high flows, and on the small effect at very low flows.

The pipe used in the experiment was new copper tubing, and it was considered that errors introduced by irregularities were negligible.

The calculated maximum possible error was about 35%: the sum of the errors in flow rates, reproducibility of flow conditions, and manometer readings. An error of this magnitude could only occur at low flow rates, where the actual flow rate, which contributed so heavily to the error,

was quite indefinite. This figure for maximum error covers the scattering of points on the plots, which is serious only at low flow rates.

The fact that a large majority of the data gave results that were very consistent when plotted indicates that the overall precision of the measurements and methods was good. The similarity between Fig. 6 and Fig. 7 for Configuration C, which should be mirror images, is a good check on the reproducibility of the flow conditions and of the measurements. Points calculated from low flow rates and high ratios of separation in flow tend to be scattered, because the precision is less in this range.

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