Chapter 6

Experimental Results and System Model Validification

6.1 Experimental Results

The experiments are set in Table 5.4 . The results are shown in Tables 6.1, 6.2 and 6.3 and are plotted in Fig. 6.1

The bed temperature T_B is the average temperature calculated from the temperatures measured by themocouple TC1 and TC2 at a certain time. The gas temperature T_G is measured by thermocouple TC3 which is above the bed. When the bed is in steady state, the bed temperature and the gas temperature at this steady state are $\bar{T}_B$ and $\bar{T}_G$.

The superficial velocity at room temperature U_{orm} is transformed into the superficial velocity at steady state bed temperature U_o by calculation using the perfect gas law.

Concentration of oxygen in the freeboard is measured by orsat and assumed to be the concentration in the bubble at the bed height, C_{Ab}

The carbon overflow rate F_{1c} and the carbon elutriation rate F_{2c} are calculated from the coal ash flow rates in overflow and elutriation respectively and the ultimate analysis of carbon content left in the coal ash collected from the experiments.

Calculations of air-to-fuel ratios and excess air are shown in Appendix E and Appendix F respectively.

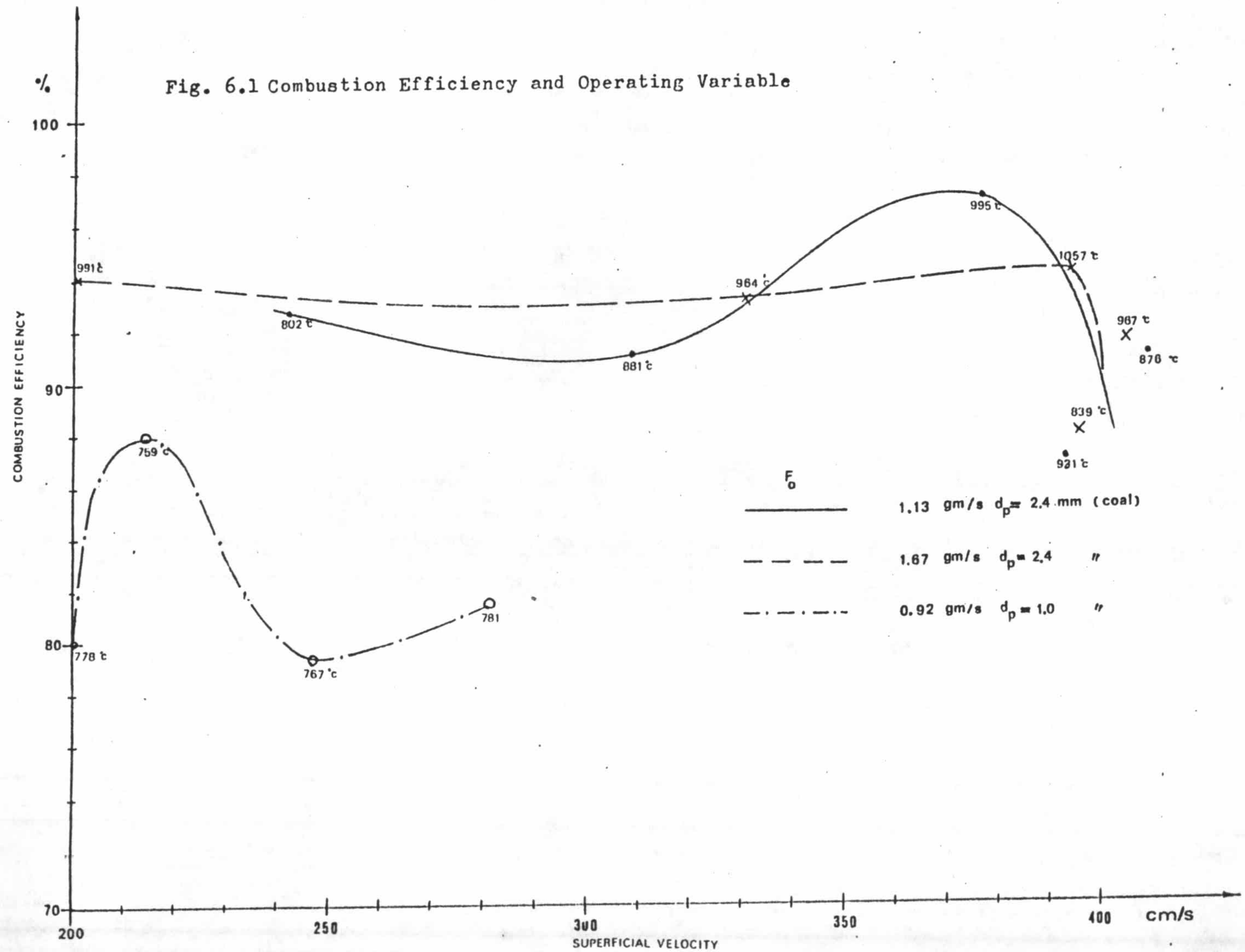


Fig. 6.1 Combustion Efficiency and Operating Variable

Table 6.1 Results of Series 1 Experiments

run Series 1 average lignite particle diameter = 0.24 cm, coal feed rate = 1.1314 gm/s L_f = 30 cm

percent of carbon in coal = 41.48 % carbon feed rate = 0.4693 gm/s d_t =15 cm

Data No	U_{orm} cm/s	Time hr:mn:s	T_B °C	T_G °C	$\bar{T}_B$ °C	$\bar{T}_G$ °C	U_o cm/s	F_{1c} gm/s	F_{2c} gm/s	η_c %	air/fuel ratio	excess air %	SO_2 PPM	O_2 %	CO PPM	Re_c
1	64.732	0:0:0	748	385												
		0:31:0	802	389	802	389	242.09	0.0228	0.0113	92.73	13.08	160.41	20	21	6026	12,589
2	72.823	0:20:0	848	424												
		0:37:0	915	421	881	422	307.83	0.0390	0.0039	90.85	14.70	208.45	65	20.5	3514	14,784
3	80.920	0:0:0	976	408												
		0.34:0	983	419												
		0.36:0	992	416												
		0.37:0	1005	418	995	418	375.85	0.0028	0.0120	96.85	16.34	242.75	78	19	1561	18,236
4	89.00	0:0:0	864	425												
		0:75:0	821	410												
		0:31:0	909	412												
		0:33:0	931	409	931	409	392.51	0.0391	0.0250	86.35	17.96	276.97	68	18	1186	19.311
5	97.10	0:0:0	834	419												
		0:28:0	867	408												
		0:30:0	885	417	876	412	408.67	0.0074	0.0349	91.00	19.60	311.28	64	19	1307	20,026

U_{orm} = superficial velocity of air at ruomtemperature,

U_o = superficial velocity of air at bed temperature T_B

T_B = bed temperature

$\bar{T}_B$ = average steady state bed temperature

T_G = flue gas temperature

$\bar{T}_G$ = average steady state gas temperature,

d_t = bed diameter

F_{oc} = carbon feed rate of coal

F_{1c} = carbon overflow rate of coal

F_{2c} = carbon elutriation rate of coal

η_c = carbon combustion efficiency

C_{o2} = oxygen concentration of flue gas in free-board

L_f = expanded bed height

Re_c = Reynolds number of combustor column

Table 6.2 Results of : Series 2 Experiments

Run Series 2, average lignit particle diameter = 0.24 cm, coal feed rate = 1.6717 gm/s L_f = 30 cm

Percent of carbon in coal =41.48% , carbon feed rate=0.6934 " d_t = 15 cm

Data No.	U_{orm} cm/s	Time hr:min:s	T_B C	T_G C	T_B C	$\bar{T}_G$ C	$\bar{U}_o$ cm/s	F_{1c} gm/s	F_{2c} gm/s	η_c %	air/fuel ratio	exass air,%	SO_2 PPM	O_2 %	NO PPM	CO PPM	Re_c
1	64.73	0:36:0	995	423													
		0:37:0	990	421													
		0:43:40	988	421	991	420	200.70	0.0164	0.0237	94.22	8.86	85.56	70	21	56	4183	9,694
2	78.82	0:32:0	1064	421													
		0:35:0	1057	423													
		0:39:0	975	430													
		0:41:0	987	432	964	430	329.96	0.0217	0.0256	93.17	9.94	108.75	68	21	25	6366	15,541
		0:54:0	930	430													
3	80.92	0:30:0	1025	449													
		0:48:0	1057	454	1057	454	394.23	0.0107	0.0292	94.25	11.06	131.98	52	20.5	14	7638	17,543
4	89.01	0:25:0	950	437													
		0:29:0	940	446													
		0:37:0	967	445	967	445	404.29	0.0190	0.0388	91.67	12.16	155.16	55	21	22	4183	18.355
5	97.10	0:15:0	951	430													
		0:18:0	958	428													
		0:21:0	914	420													
		0:33:0	839	404	839	404	395.51	0.0186	0.0651	87.94	13.62	178.35	52	20.5	–	2246	19,814

Table 6.3 Results of Series 3 Experiments

Run Series 3, average lignite particle diameter =0.095cm coal feed rate = 0.9232 gm/s L_f =30 cm

Percent of carbon in coal = 41.46% carbon feed rate= 0.3832 gm/s d_t =15 cm

Data No.	U_{orm} cm s	Time hr:min:s	T_D °c	T_G °c	$\bar{T}_B$ °c	$\bar{T}_G$ °c	$\bar{U}_o$ cm/s	F_{1c} gm/s	F_{2c} gm/s	η_c %	air/fuel ratio	excrs air,%	SO_2 PPM	O_2 %	CO PPM	Re_c
1	51.79	0:40:0	772	290												
		0:47:0	782	294												
		0:52:0	778	295												
		0:59:0	777	299	778	295	199.38	0.0665	0.0116	79.64	12.80	168.66	26	21	7818	13,259
2	56.64	0:30:0	762	295												
		0:34:0	759	294												
		0:36:0	757	293	759	294	214.11	0.0443	0.0189	88.21	14.02	193.82	23	18.5	5623	14,260
3	64.73	0:30:0	770	306												
		0:36:0	772	312												
		0:42:0	760	315												
		0:47:0	765	314	767	312	246.59	0.0625	0.0269	79.48	16.02	235.79	24	19	5534	15,659
4	72.82	0:30:0	780	323												
		0:39:0	781	319												
		0:41:0	782	317	781	319	281.14	0.0352	0.0352	81.64	18.02	277.75	24	19	3935	17,515

6.2 System Model Validification

The carbon combustion efficiencies calculated from the proposed system model are compared with experimental results and presented in Table 6.4

The average absolute relative deviation of computed carbon combustion efficiencies from the experimental values $|\Delta\eta|$ are 1.7 %, 1.5 % and 3 % for run series 1,2, and 3 respectively. These small relative deviations show that the system model developed is in good agreement with the experimental results.

6.3 SO_2 and NO emission

In the experiments, the molar ratio of Ca: S in the fuel mixture is 12 : 1. And the SO_2 emissions from the experiments are shown in Table 6.1, 6.2 and 6.3. The average SO_2 emission is 50 PPM which is much lower than 500 PPM, the acceptable emission standard.

From Table 6.2 the average NO emission from the experiment is about 30 PPM under the bed temperature between 950-1050°C, which is very low when compared with the acceptable emission standard of 500 PPM.

6.4 Change of Bed Temperature with Air-to-fuel Ratio

Fig. 6.2 shows the bed temperature as a function of air-to-fuel ratio for several feed rates and average lignite particles diameter. The bed temperatures are between 750-1050°C. The bed temperature

TABLE 6.4

Comparison of Experimental and

Predicted Combustion Efficiencies of Lignite for

Atmospheric Pressure Fluidized Bed Combustion

Run No.	Data No.	$\bar{d}_p$ lignite (cm)	$\bar{d}_p$ limestone (cm)	F_{ocl} gm/s	U_o (cm/s)	XS AIR(%)	$\frac{\text{air}}{\text{fuel}}$ (by wt.)	T_B °K	η (%) exp.	η (%) calc.	$\Delta\eta$	$\overline{\|\Delta\eta\|}$
1	1	0.2401	0.0927	1.1314	242.09	160.41	13.08	1075	92.73	92.04	-0.69	
	2	"	"	"	307.83	208.45	14.70	1154	90.85	88.77	-2.08	
	3	"	"	"	375.85	242.75	16.34	1268	96.85	95.14	-1.71	
	4	"	"	"	392.51	276.97	17.98	1204	86.35	87.77	+1.42	
	5	"	"	"	408.07	311.28	19.60	1149	91.00	93.83	+2.83	1.746
3	1	"	"	1.6717	299.70	85.56	8.86	1264	94.22	94.39	+0.17	
	2	"	"	"	329.96	108.75	9.94	1237	93.17	93.49	+0.32	
	3	"	"	"	394.23	131.98	11.06	1330	94.25	94.32	+0.07	
	4	"	"	"	404.29	155.16	12.16	1240	91.67	93.12	+1.45	
	5	"	"	"	395.51	178.35	13.62	1112	87.94	93.27	+5.33	1.468
5	1	0.0954	0.0600	0.9236	199.38	168.66	12.80	1051	79.64	82.66	+3.02	
	2	"	"	"	214.11	193.82	14.02	1032	83.50	88.21	+4.71	
	3	"	"	"	246.59	235.79	16.02	1040	76.69	79.48	+2.79	
	4	"	"	"	281.14	277.75	18.02	1054	81.64	80.14	-1.50	3.005

Stichiometric of air fuel ratio of lignite = 4.78

$\bar{d}_p$ = average particle diameter

XS = excess air

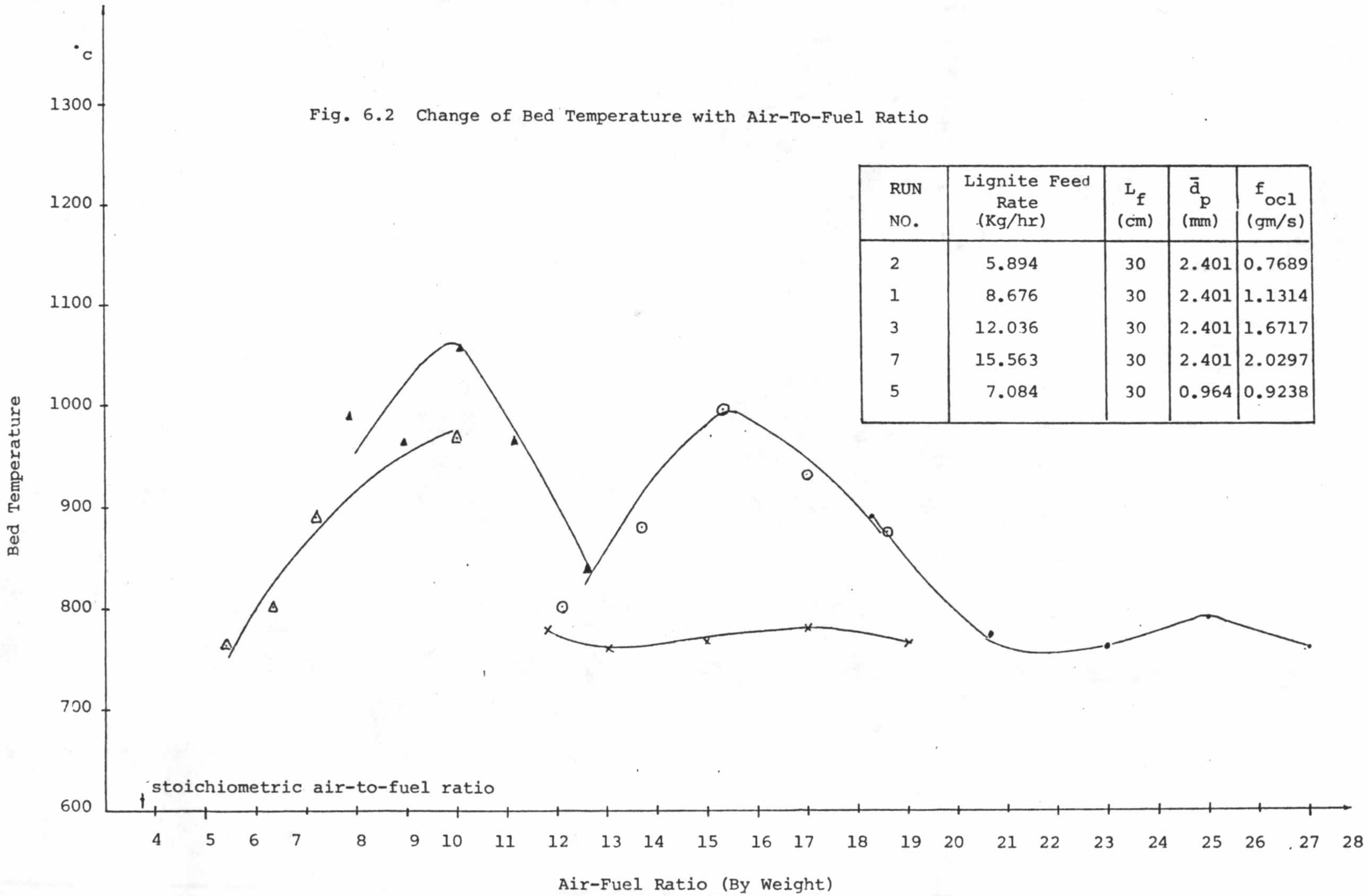
F_{ocl} = coal feed rate

$\bar{T}_B$ = average steady state bed temperature

$\Delta\eta$ = deviation of calculated carbon combustion efficiency from experimental value

$|\Delta\eta|$ = absolute deviation of calculated carbon combustion efficiency from experimental value.

Fig. 6.2 Change of Bed Temperature with Air-To-Fuel Ratio



RUN NO.	Lignite Feed Rate (Kg/hr)	L_f (cm)	$\bar{d}_p$ (mm)	f_{ocl} (gm/s)
2	5.894	30	2.401	0.7689
1	8.676	30	2.401	1.1314
3	12.036	30	2.401	1.6717
7	15.563	30	2.401	2.0297
5	7.084	30	0.964	0.9238

increases as the air-to-fuel ratio increases until the maximum temperature is reached, then decreases.

The minimum air-to-fuel ratio with which the bed can sustain self combustion in the fluidizing state throughout the bed is about 6 which is heigher than the stoichiometric air-to-fuel ratio by 30 %.

6.5 Carbon Particle Interaction

Since the char particles in the bed comprise about 0.1 % and 0.23 of run series 1 and series 2 respectively (see Table 6.5) the carbon particle interaction should be small and corresponding to single-particle Sherwood number correlation used in the model.

6.6 Reynolds Number of Combustor Column

The combustor column Reynolds number in these experiments are between 9,000 and 20,000 and shown in Fig. 6.3. The gas density is not constant due to the combustion of coal in the bed. These can be used to predict the gas flow on the column surface (laminar or turbulent flow)

6.7 Carbon Monoxide (CO)

From Table 6.1 and 6.2 the average concentration of CO in the flue gas is 3,826 PPM or 0.38 %. If the carbon combustion efficiency is 95 %, carbon feed rate is 0.7 gm/s, and superficial velocity of air is 3.5 m/s at STP, the complete reaction in the reactor would produce only CO_2, but in fact from the experiment CO is about 0.38 %, hence the uncomplete combustion is about 19 % of the complete one. At higher temperature than 700°C, CO may come from the endothermic reaction of

$$CO_2 + C \longrightarrow 2CO$$

This reaction increases with increased bed temperature

6.8 Bed Temperature and Coal Feed

From Fig 6.1, the graph corresponding to 1.0 mm particles is lower than other graphs.It is to be noticed that the bed temperature shown in this graph is lower than the other ones in those two graphs. The lower bed temperature may be affected by unsufficiently feeding of coal.

Table 6.5 Calculated Data Based on Bed Particles (Limestone)

Run No.	Data No.	$\bar{d}_p$ limestone cm	U_o cm/s	T_B °K	U_{mf} cm/s	$\frac{U_o}{U_{mf}}$	d_b cm	$(K_{bp})_b$ s^{-1}	X_b	C_{AP} gm-mole/cm^3	W_B gm	F_{ocl} gm/s	W_{cl} gm	$\frac{W_{cl}}{W_B}$x100 %	$\bar{t}$,s W_{cl}/F_{ocl}	η %
1	1	0.0927	242.09	1075	68.65	3.53	15	21.07	2.434	2.38×10^{-6}	6797.0	1.1314	6.67	0.098	5.890	92.04
	2	"	307.83	1154	65.89	4.67	15	21.35	1.952	2.16×10^{-6}	6685.7	"	6.08	0.091	5.372	88.77
	3	"	357.85	1268	62.24	6.04	15	20.38	1.529	1.74×10^{-6}	6636.8	"	6.64	0.100	5.270	95.14
	4	"	392.51	1204	64.29	6.11	15	20.92	1.514	1.73×10^{-6}	6563.1	"	6.69	0.102	5.192	87.77
	5	"	408.67	1149	65.92	6.19	15	21.36	1.494	1.91×10^{-6}	6497.7	"	6.69	0.103	5.915	93.83
3	1	0.0927	299.70	1264	67.37	4.45	15	21.91	2.064	2.02×10^{-6}	6794.8	1.6717	9.26	0.136	5.54	94.39
	2	"	329.96	1237	63.25	5.22	15	20.65	1.755	2.07×10^{-6}	6699.3	"	8.93	0.133	5.34	93.49
	3	"	394.23	1330	60.46	6.52	15	19.91	1.422	1.89×10^{-6}	6648.4	"	8.66	0.130	5.18	94.32
	4	"	404.29	1240	63.14	6.40	15	20.62	1.447	2.06×10^{-6}	6570.5	"	8.37	0.127	5.00	93.12
	5	"	395.51	1112	67.16	5.89	15	21.68	1.569	2.21×10^{-6}	6465.1	"	8.85	0.137	5.29	93.27
5	1	0.06	199.38	1051	26.68	7.47	15	9.47	1.097	2.15×10^{-6}	6778.8	0.7238	1.49	0.022	1.61	82.66
	2	"	214.11	1032	27.73	7.72	15	9.76	1.074	2.04×10^{-6}	6720.4	"	1.65	0.021	1.79	88.21
	3	"	246.54	1040	27.41	8.99	15	9.67	0.950	2.11×10^{-6}	6642.3	"	1.42	0.023	1.54	79.48
	4	"	281.14	1039	26.62	10.56	15	9.45	0.832	2.07×10^{-6}	6575.3	"	1.41	0.022	1.53	78.36

W_B = weight of bed material

W_{cl} = weight of coal in bed

$\bar{t}$ = average coal particle resident time in bed

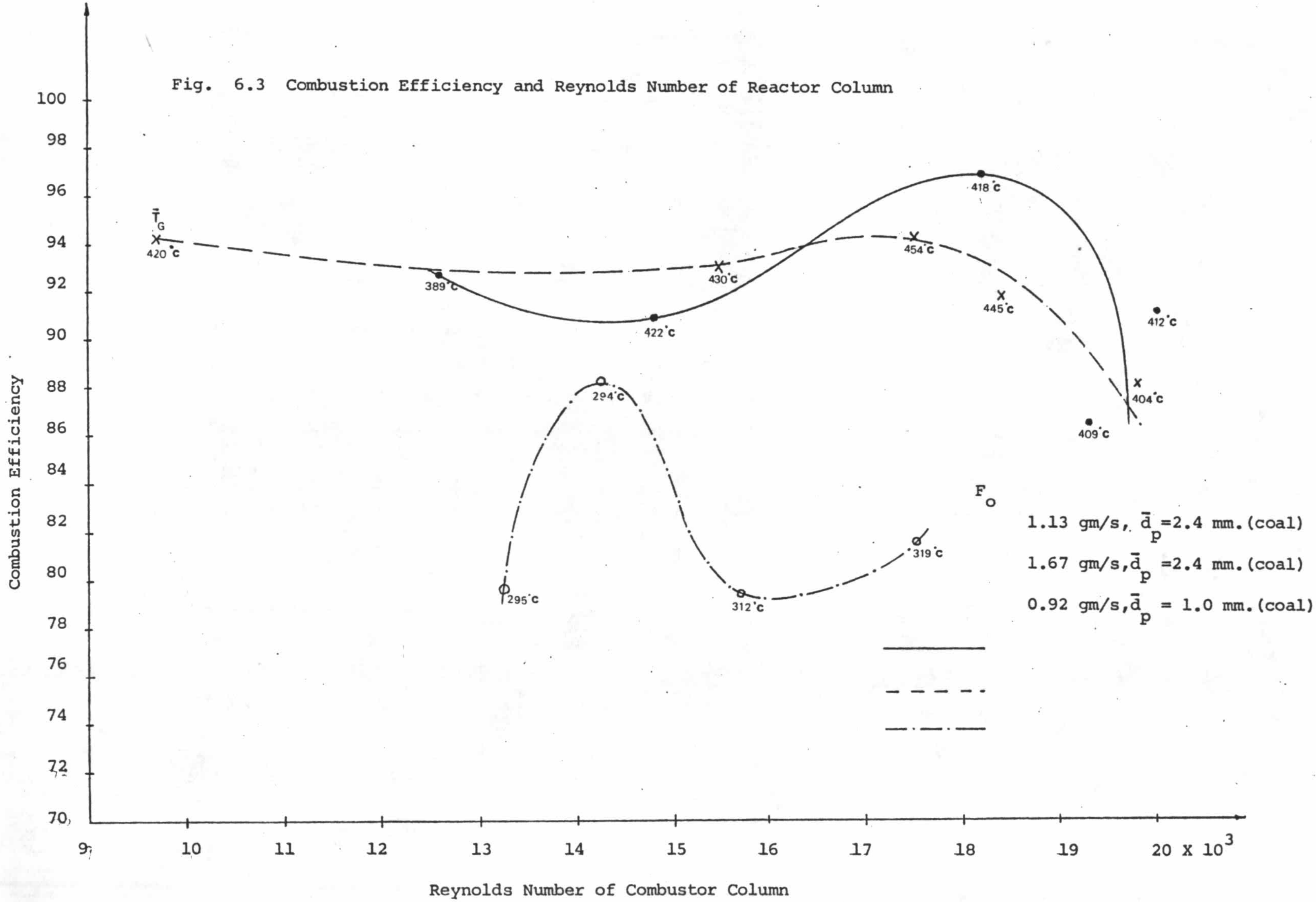


Fig. 6.3 Combustion Efficiency and Reynolds Number of Reactor Column