DIAGNOSTICS AND MODELING

Design of Experiments

OVERVIEW

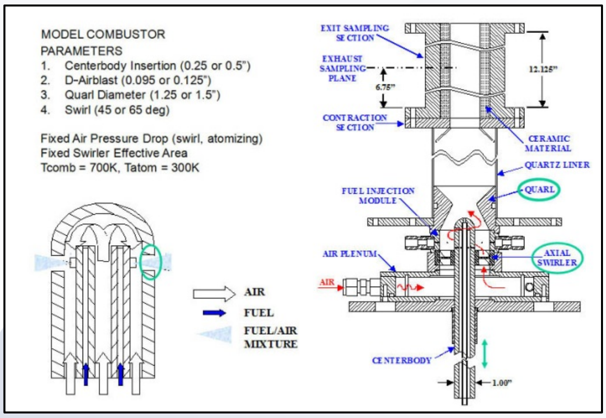
Due to the highly interdisciplinary nature of combustion science, planning both physical and numerical experiments can be quite challenging to develop in a manner that reveals the key factors affecting a component or system. Often, a large number of “independent”variables (e.g., fuel/air ratio, temperature, pressure, mixing, fuel type, etc.) that might influence the process of interest (e.g., pollutant emissions, stability, acoustics, etc.) can be identified. As a result, an efficient methodology for which to study the effects of these factors is almost a necessity. To this end, coupling statistics with engineering has led to an increased utilization of so called statistically designed experiments or “Design of Experiments or DOEx.” When applied correctly, DOEx can help to (1) focus the development of a test plan, (2) maximize the efficiency with which a test campaign can be carried out, and (3) provide important insights into how various factors studied may actually interact with each other. This methodology often leads to a quick assessment of which factors are most important in the process. Often, the goal of a study is to simultaneously maximize the “value” of multiple responses (e.g., low NOx emissions, low CO emissions, and good lean stability). As a result of the DOEx methodology, optimization strategies for maximizing the process value through a combination of factors are also available. This powerful methodology is becoming commonplace in industry (e.g., six-sigma practices) as a means to improve and refine processes and overall quality of products.

OBJECTIVES

The UCICL commonly applies DOEx to help guide both experimental and numerical studies. A major motivation is to apply DOEx to screen which factors affect processes in order to focus the next set of studies on the parameters that matter the most. This approach can be used in the design of a premixer, combustor, fuel injector, or any combination thereof.

RESULTS

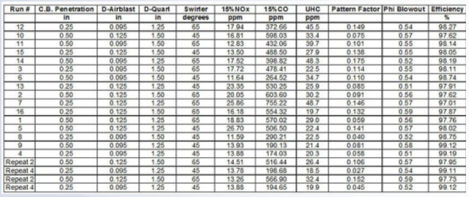
Examples of results obtained are shown below. In this example, a model combustor (shown in Figure 1) is used and its performance is assessed as impacted by changes in key geometrical features. In this case, the axial insertion of the centerbody, the diameter of the airblast atomizing air hole, the inner diameter of the quarl, and the swirl strength are all varied systematically. The air pressure drop for both combustion air and air-blast air are fixed as they would be in practice. In addition, the firing rate is fixed. Figure 2 summarizes the combindations of parameters studied along with the measured results (NOx, CO, UHC, Pattern Factor, equivalence ratio at blowoff). In this system, it is desired to simultaneously minimize all of these responses. Note that several of the combinations of factors are studied multiple times which helps to establish overall ncertainty/repeatability of the experimental setup.



MODEL COMBUSTOR PARAMETERS
1. Centerbody Insertion (0.25 or 0.5”)
2. D-Airblast (0.095 or 0.125”)
3. Quarl Diameter (1.25 or 1.5”)
4. Swirl (45 or 65 deg)

Fixed Air Pressure Drop (swirl, atomizing)
Fixed Swirler Effective Area
Tcomb = 700K, Tatom = 300K

Figure 1. Model Combustor



Run #	C.B. Penetration	D-Airblast	D-Quarl	Swirler	15% NOx	15% CO	UHC	Pattern Factor	Phi Blowout	Efficiency
	in	in	in	degrees	ppm	ppm	ppm			%
12	0.25	0.095	1.25	65	17.94	372.66	45.5	0.149	0.54	98.27
10	0.50	0.125	1.50	45	16.81	598.03	33.4	0.075	0.57	97.62
11	0.50	0.095	1.50	65	12.83	432.06	39.7	0.101	0.55	98.14
15	0.25	0.125	1.50	45	13.50	488.50	27.9	0.138	0.55	98.05
14	0.50	0.095	1.25	65	17.52	398.82	48.3	0.175	0.52	98.19
3	0.25	0.095	1.50	65	17.72	478.41	22.5	0.114	0.55	98.11
6	0.50	0.095	1.50	45	11.64	264.52	34.7	0.110	0.54	98.74
13	0.25	0.125	1.25	45	23.35	530.25	25.9	0.085	0.51	97.91
2	0.50	0.125	1.50	65	20.05	603.60	30.2	0.091	0.56	97.62
7	0.25	0.125	1.25	65	25.86	755.22	48.7	0.146	0.57	97.01
16	0.25	0.125	1.50	65	16.18	554.32	19.7	0.132	0.59	97.87
1	0.50	0.125	1.25	65	18.83	570.02	29.0	0.059	0.56	97.76
5	0.50	0.125	1.25	45	26.70	506.50	22.4	0.141	0.57	98.02
8	0.25	0.095	1.50	45	11.59	290.21	22.5	0.040	0.52	98.75
9	0.50	0.095	1.25	45	13.93	190.13	21.4	0.081	0.58	99.12
4	0.25	0.095	1.25	45	13.88	174.03	20.3	0.058	0.51	99.19
Repeat 2	0.50	0.125	1.50	65	14.51	516.44	26.4	0.106	0.57	97.95
Repeat 4	0.25	0.095	1.25	45	13.78	198.68	18.5	0.027	0.54	99.11
Repeat 2	0.50	0.125	1.50	65	13.26	566.90	32.4	0.152	0.59	97.73
Repeat 4	0.25	0.095	1.25	45	13.88	194.65	19.9	0.045	0.52	99.12

Figure 2. Measured Results

Each response is analyzed using analysis of variance. The results of the analysis of variance in this case are illustrated in the half-normal plot shown in Figure 3. In this figure, random variations in results will distribute themselves normally (i.e., according to Gaussian or normal statistics). Variations that fall away from the normal distribution are statistically influencing the process. In this case, efficiency is examined. The analysis of variance indicates that factor B and D are important, namely the air-blast diameter hole size and swirl strength.

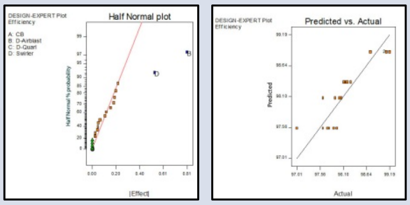


Figure 3. Half Normal Response Plot

The analysis of the results leads directly to a model for the efficiency as a function of these two factors:

Efficiency = 102.7 - 27.1*D-Airblast - 0.03*Swirler

As shown, an increase in the diameter of the air-blast air hole and an increase in swirl reduces combustion efficiency. This is due to the fact that (1) the air-blast atomizing air is not preheated and therefore slows evaporation of the fuel spray and (2) the high swirl leads to more mass flux towards the walls, leading to quenching and higher emissions of CO and UHC.

Each response (NOx, CO, UHC, lean blow off equivalence ratio, and pattern factor) should be minimized for best performance. Each response is analyzed and a model response generated. Using the modeled responses, a cost function analysis can be carried out which can guide the design. Figure 4 summarizes the general combination of factors that leads to the best performance. As shown, lower swirl is preferred along with a 1.5” quarl i.d., a smaller diameter air-blast hole diameter, and a small centerbody insertion.

Number	CB	D-Airblast	D-Quarl	Swirler
1	0.25	0.095	1.50	45.06
2	0.25	0.095	1.49	45.21
3	0.25	0.095	1.45	45.00
4	0.26	0.096	1.50	45.02
5	0.25	0.095	1.37	45.00
6	0.25	0.095	1.34	45.00
7	0.25	0.095	1.28	45.00
8	0.25	0.100	1.46	45.07
9	0.25	0.095	1.50	52.65
10	0.42	0.095	1.50	45.00

Figure 4. Optimization Results.

PUBLICATIONS

IMPACT OF ETHANE & PROPANE VARIATION IN NATURAL GAS ON THE PERFORMANCE OF A MODEL GAS TURBINE COMBUSTOR (2003). ASME J. Engr. Gas Turbines and Power, Vol. 125, No. 3, pp. 701708 (R.M. Flores, V.G. McDonell, and G.S. Samuelsen)

AUTOIGNITION CORRELATIONS FOR PIPELINE NATURAL GAS AT LOW AND INTERMEDIATE TEMPERATURES (2007). *AIAA J. Prop. and Power*, Vol 23, No. 3, pp. 585-592. (J.H. Chen, V.G. McDonell, and G.S. Samuelsen)

IMPACT OF ETHANE, PROPANE, AND DILUENT CONTENT IN NATURAL GAS ON THE PERFORMANCE OF A COMMERICAL MICROTURBINE GENERATOR (2008). *ASME J. of Engineering for Gas Turbines and Power,* Vol 130, Jan. pp. 011509-1 – 011506-7 (R.L. Hack and V.G. McDonell).

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