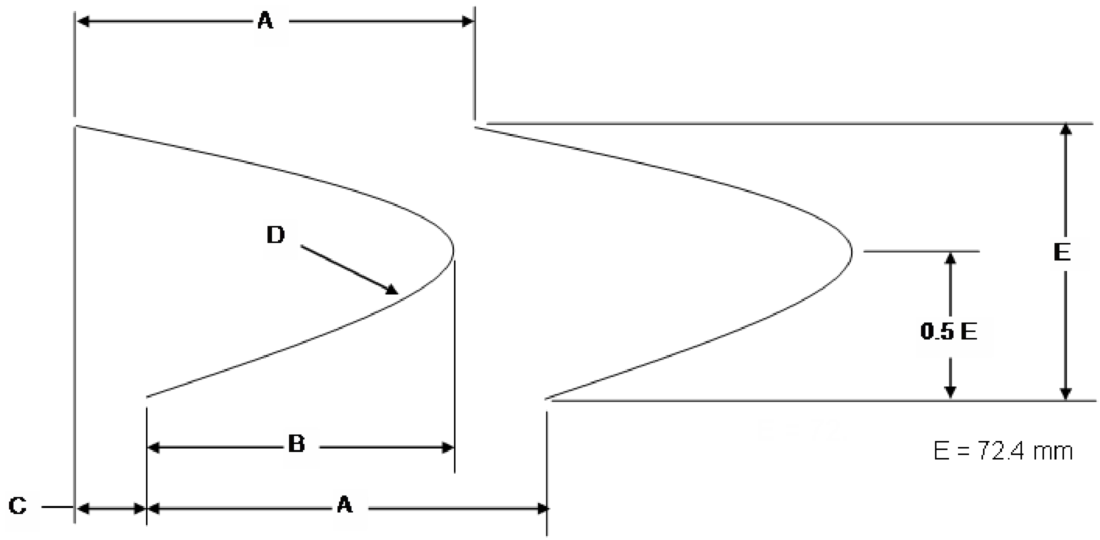
Design of Experiments Reduces Time Required to Optimize Complex Design

The traditional approach to optimizing a product or process using computer simulation is to evaluate the effects of one design parameter at a time. Then after it has been optimized the analyst moves to the next variable. The problem with this approach is that interactions between design factors and second order effects mean that this approach is likely to lead down a blind alley. It will result in a locally optimized design that will provide far less performance than the global optimum. Another problem is that many types of simulation take a considerable amount of time, even days, to evaluate a single design iteration. So there is only time to evaluate a small subset of the design space. For these reasons, a number of analysts have begun using design of experiments (DOE) via Response Surface Methods (RSM) to drive the design process. DOE/RSM can be used to develop experiments that examine first order, second order, and multiple factor effects simultaneously with relatively few simulation runs. The result is that the analyst can iterate to a globally optimized design with a far higher level of certainty and in much less time than the traditional approach. This article will show how Dan Cler, Senior Mechanical Engineer for Benét Laboratories, Watervliet, New York, is using DOE/RSM to design a new generation of muzzle brakes.

Challenge of optimizing design over many variables

One of the centerpieces of the Army's Future Combat Systems (FCS) program is the development of new combat vehicles that are only about one-fourth to one-half the weight of the Army's current vehicles, yet capable of mounting guns as powerful as the older vehicle's guns. To meet this goal, the new lighter vehicles require muzzle brakes that redirect part of the gun's propellant flow backwards to reduce the gun's recoil. But this redirection must be accomplished while keeping the blast overpressure on the vehicle itself low enough to prevent vehicle damage and injury to nearby soldiers. Testing proposed muzzle brake designs is very expensive and time-consuming. The engineers at the Army's Benét Laboratories are therefore using a new generation of computational fluid dynamics (CFD) software to model the gun's recoil forces and blast pressures for different muzzle brake designs to provide a design with low recoil force and acceptable blast overpressure. They face the challenge that there are many possible design parameters that can affect the performance of the muzzle brake and evaluating just one combination of design parameters can take a considerable amount of time because of the complexity of the analysis task.



Factor	Name	Units	Type	Low Actual	High Actual
A	Opening Width	mm	Numeric	95	125
B	Offset	mm	Numeric	50	70
C	Exit Offset	mm	Numeric	0	30
D	Shape Factor	mm	Numeric	0.5	0.8

Design Variable	Design Value
Study Type	Response Surface
Initial Design	D-optimal
Point Selection	Point Exchange
Design Model	Cubic
Runs	51
Blocks	3

Figure 1: Design variables or factors

Cler is addressing this challenge by using designed experiments that require a relatively small number of simulation runs. Each simulation run uses a simplified two-dimensional model to explore the entire design space. This method identifies the area of optimal design and then Cler builds a more detailed three-dimensional model and explores this small area without having to pay attention to the vast areas that DOE/RSM has ruled out. Figure 1 shows the design parameters, or factors in DOE/RSM terminology, for a typical muzzle brake. Cler selected a D-optimal design to provide an ideal set of experimental combinations for fitting a cubic predictive model with a minimum number of design points.

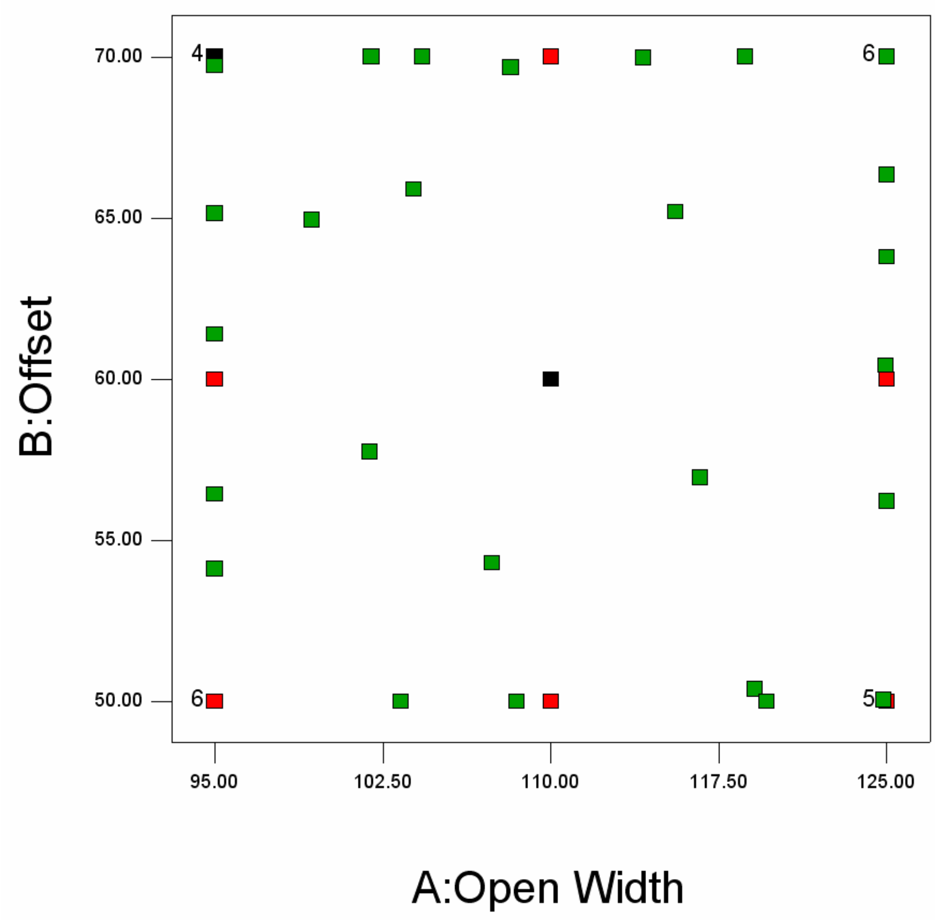


Figure 2: Designed experiment

Simplifying the DOE/RSM method

"We selected Design-Expert® DOE/RSM software from Stat-Ease, Inc., Minneapolis, Minnesota, because it is a research-grade software package," Cler said. "Design-Expert provides a wide range of experimental designs and statistical analyses that go far beyond what is offered by general statistical packages. Design-Expert also greatly simplifies DOE/RSM by making it easy for a user without statistical background to design an experiment and analyze the results." The experiment designed by Design-Expert and shown in Figure 2 focuses on the edges of the design space while also including some points in the middle. The points tend to be evenly spaced in order to reduce colinearity. An important characteristic of physical experiments is that they are subject to natural process variations so they are not deterministic. Numerical simulations, on the other hand, generally provide exactly the same answer every time. A designed experiment based on physical experiments includes repeat runs to estimate the error but this is not applicable to the simulation world. Stat-Ease recommends adding extra design points to compensate for the absence of error points.

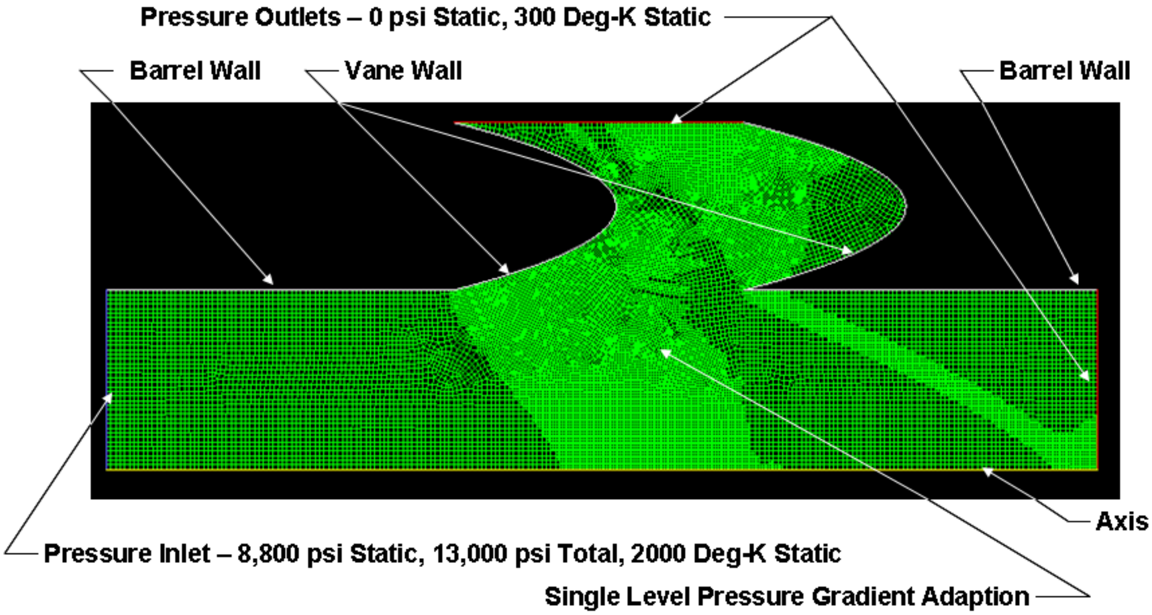


Figure 3: CFD grid and boundary conditions

Benét Laboratories uses FLUENT CFD software from ANSYS, of Canonsburg, Pennsylvania, to simulate the operation of the muzzle brake. FLUENT uses static adaption to change the density of the mesh throughout the domain so that shocks in the muzzle brake are properly resolved. Comparing 3-D simulation predictions to physical testing has shown that CFD accurately predicts forces generated on the muzzle brake during blow-down of the propellant gases after the projectile leaves the gun barrel. For the 2-D simulations utilized in the 51-run design, complete convergence was not possible in all cases due to flow instabilities in some of the configurations. This is one of the difficulties in performing designed experiments. Often the design points selected do not always provide acceptable results.

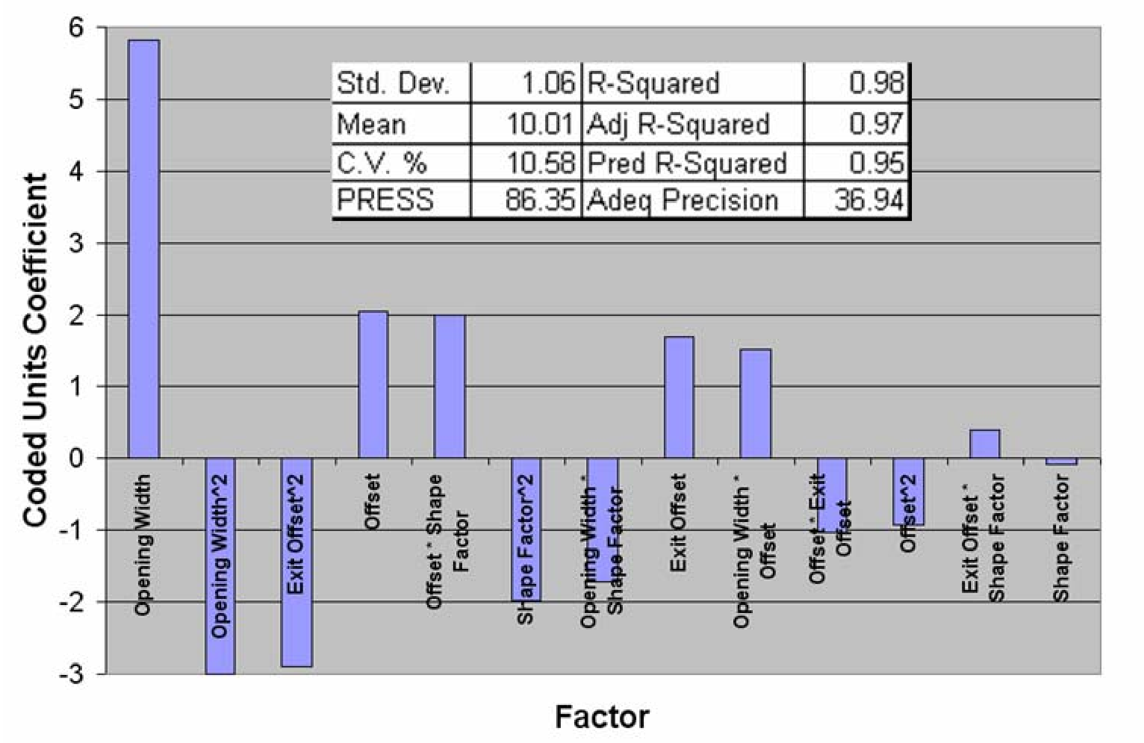


Figure 4: ANOVA results from designed experiment

DOE results expedite optimization of design

Cler used two key responses in this designed experiment. Axial momentum is the product of the axial velocity and the density of the gas. Essentially, it determines the change in direction provided by the muzzle brake. The other response is the mass flux ratio or the mass flux through the vane of the muzzle brake divided by the mass flux through the barrel. Physically, this represents the proportion of the flow emitted by the barrel that is redirected by the muzzle brake. The design objective is to maximize both responses in order to reduce recoil. Figure 4 above shows the analysis of variance (ANOVA) results for first and second order two-factor interaction effects of each factor on the mass flux ratio. The ANOVA results separate the factors that have the greatest impact from those that have a minimal impact on the responses. In this case, the opening width has the greatest impact while the shape factor appears to be insignificant.

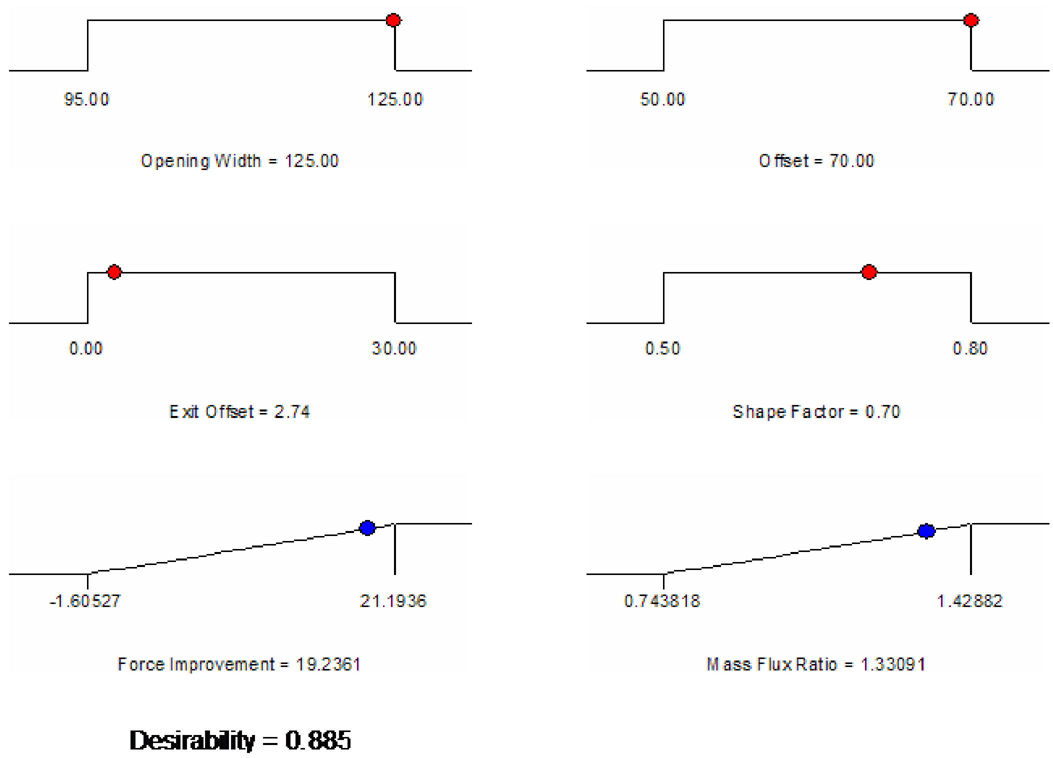


Figure 5: Optimal values provided by Design-Expert® software.

Figure 5 shows the optimal values for each factor calculated by Design-Expert in this application. The true power of DOE/RSM resides in its ability to optimize a design across many variables. The response surface method explores the entire design space and so avoids the common problem of getting stuck in a local optimum by not taking second order and multiple factor interactions into account. In this case, DOE/RSM quickly and efficiently zeroed in on the area of the design space containing the optimum. It also provided expected values as well as confidence intervals for the responses with the factors optimized. The next step was to manually perform a more detailed and time-consuming analysis of this small area of the design space. “DOE has proven to be a very effective method for exploring the complex design space of our products,” Cler said. “DOE does not replace the judgment and experience of the engineer. But by eliminating the vast majority of the design space from consideration, DOE enables the engineer to focus his or her attention on the critical areas where he or she can have the most impact.”

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