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Specifying Thermal Components - Making a Great Gumbo
Like making a great gumbo stew, when specifying thermal components, it's essential to take a systems approach

by Christopher C. Lanham
A common mistake made when specifying thermal components is to not adequately consider how a component interacts with its environment and with other components in the system. For example, engineers often request heaters with very specific temperature uniformity, without understanding that temperature uniformity is not a heater component attribute (power dissipation is a heater attribute). Similarly, when a new thermal system design fails to control temperature within desired tolerances, it is often concluded that the accuracy or precision of the PID control unit is the problem. However, more often the sensor or heater response is unstable due to mechanical fit problems. In order to make the best thermal component choice for any given application, and avoid chasing your tail during new equipment checkout, it is essential to remember that a system's performance is not simply the sum of the performance of each individual component. Even for very simple thermal systems, taking the time to develop a complete system can dramatically reduce design cycle time and development costs. Such an approach can eliminate many of the potential headaches caused by trying to “back in” to a thermal system, one component at a time.

In its most basic form, a thermal system consists of the following major components:

•**Work Load** – The item to be heated.
•**Heat Transfer Medium** – The materials and environment that must transfer heat to and from the work load.
•**Heat/Cool Source** – The item that converts the input power source into heating/cooling energy.
•**Process Temperature Sensor** – The item that indicates the temperature of the work load.
•**Process Temperature Control** – The item that regulates the temperature of the work load.
•**Power Control** – The item that connects/disconnects input power to the heat/cool source as determined by the process temperature control.

When schedules are short, design engineers frequently dive right into the specific characteristics of one particular component, while committing little effort toward understanding the interrelationship between it and other items. Just as the interplay of spices provide a richness' of flavor to a dish of gumbo, power dissipation across a heater surface is just one 'ingredient' that of temperature uniformity within a thermal system. A heat/cool source can be designed such that the system attribute of temperature uniformity emerges, provided that the source is combined with the system's other components in a very specific and controlled manner. Defining the relationship of system components such that the desired system performance emerges is the primary challenge when describing a thermal system.

Describing the System

All system development should start with a clear statement of need from the user's perspective. When starting a dish of gumbo, the statement of need might be “I would like something spicy to eat for lunch.” For an example relevant to thermal systems, consider planning the design of an extrusion plastometer, which is an analytical device used to determine the melt properties of plastics or polymers. The statement of need for an extrusion plastometer might be “I would like to control the temperature of the sample in my extrusion plastometer to ±1% T at set point.”

Once the need has been clearly established, a system description begins by defining the behavior of the system needed to fulfill that need. Behavior can be described in “what it does” terms or the activities needed to be performed. For our lunch need, one characteristic of behavior is taste - in this case spicy. For our extrusion plastometer need, one characteristic of behavior is temperature uniformity - in this case ±1%.

Often behavior is referred to as function and is defined in a functional specification describing the following:

•**Mission** – objectives to be fulfilled, information to be collected or received, plan or process to be followed and degree of cooperation with others in the environment.

•**Viability** – the extent the system is able to maintain a separate existence in the environment.

•**Resources** – what is required for pursuit of mission and maintenance of viability.

Next, it is helpful to describe the system's structure - specifically, how it is built and how each component interconnects with others. To create a spicy lunch, the use of cayenne pepper is a good choice. Rice is a good candidate to absorb the cayenne's flavor, and shrimp and okra will round out the dish nicely. So, for a spicy lunch, gumbo is potentially a good structural solution. As for the extrusion plastometer, ±1% temperature uniformity is going to require either good load stability or excellent dynamic response. Plastometer samples are small so load changes will be small, yet the extrusion chamber needs to be large to withstand a high level of applied force. A potentially good structural solution is to heat the extrusion barrel externally with a distributed wattage band heater. This will allow the applied heat to be zoned to account for chamber end losses and will reduce the burden on control system response time.

Often structure is referred to as form and is added to a functional specification in order to create a complete system development specification. However, it is important to avoid defining a system's structure until its behavior is well defined. Quite literally, form should follow function to arrive at the best solution. For a structure definition to be complete, it should address the following:

•**Configuration** - identification of each physical element that makes up the system and its position, properties, materials and characteristics.

•**Context** - the environment acting on the system including what holds it together and works to break it apart.

•**Capability** - the level of achievement that can be expected based on internal features.

While a clear definition of behavior and structure represents a complete system description, it does not necessarily represent the best available combination of behavior and structure. To achieve the best solution, a definition of effectiveness is required.

Effectiveness is the measure of how well the system satisfies the statement of need. Without defined measures of effectiveness, there is no specific way to determine whether one particular system description is better than another, or even if a given system description is feasible. This is sometimes referred to as “fit.” What makes one gumbo better than another? And within extrusion plastometers, over what range of set-points is a ±1% temperature uniformity important? Does the uniformity need to be maintained while ramping between set-points? A good definition of “fit” or effectiveness will address three areas:

•**Performance** - the minimum acceptable limits for characteristics such as stability, responsiveness and uniformity.

•**Availability (of performance)** - the ability of the system to continue to perform under normal conditions.

•**Survivability** - the ability of the system to restore performance following abnormal conditions.

Techniques such as solution cost/benefit analysis, object modeling and simulation are system engineering approaches to measure effectiveness. With an effectiveness filter in place, the process of optimization can be employed to determine which behavior/structure combination best fits the system. In striving to achieve the temperature uniformity requirement for an extrusion plastometer, the process of optimization can be used to determine the degree of difficulty (and cost) associated with achieving the required performance with a given construction. Optimization will either determine that the band heater/extrusion barrel configuration can be controlled within acceptable limits, or discover that a different method of applying heat (structure) should be considered.

Through optimization, a clear description of the critical attributes or characteristics of the system will emerge. If the process of describing the system, defining effectiveness and optimization are successful, the emergent properties that result should closely align with the original statement of need.

Specifying a Component

When specifying a component, an understanding of system behavior, structure, effectiveness and optimization are all needed to best achieve the desired result. Of course, the need to limit the effort expended on this understanding, particularly when there appears to be a wide latitude in acceptable behavior or performance, is a practical one. The amount of care and planning needed to prepare a great gumbo in New Orleans is likely to be substantially greater than at a midwestern bar & grill.

In order to balance the effort expended (investment) against the potential benefit (return), risk must be considered. High component costs with corresponding failure expenses will dictate that a greater up-front effort is warranted. Alternately, where component costs are low and the cost of failure is insignificant, substantial up-front effort may not be necessary, and off-the-shelf or standard components may be sufficient. Yet if a component must be custom designed for an application, an up-front investment, involving the careful development of a complete system description, almost always reduces overall cost by avoiding the time and expense of iterative modifications.

Understanding Development Risk

Considering again the extrusion plastometer, the statement of need might be "each extrusion sample must be uniformly maintained at 300 F ±1%." If this need is not satisfied, the development risk is that the machine will not perform correctly and will produce inaccurate readings for melt properties. Therefore, design of the extrusion plastometer will also likely be an expensive undertaking, since the risk associated with temperature uniformity is high.

As a result, substantial investment is warranted to develop a complete system description around the statement of need. In the absence of a complete description, the desired behavior might be misidentified as a component specification for a temperature control unit. More like, the real problem is that the uncontrolled variation in the thermal contact resistance between the band heater and extrusion barrel makes the it impossible to maintain uniformity on the sample – no matter how complex or sophisticated the temperature control is. To ensure the desired uniformity is achieved on the sample, the system structure must be carefully defined with respect to all electrical, mechanical and environmental boundary conditions surrounding the sample, including how uniformity will be sensed and measured. In addition to set point and uniformity performance, other effectiveness attributes such as ramp rate, ramp time, cycle time and throughput may be important to consider.

In summary, if the risk associated with achieving a specification is high, attempting to fulfill the specification through the selection of individual components without a substantial understanding of the system is ill advised. Often, the construction of a numerical computer model for the system, which can account for the multitude of factors affecting the interfaces between components, is needed to arrive at an effective solution.

Understanding the Impact of Precision

One additional and common mistake is to levy demanding performance specifications upon individual components to account for tolerance stack-up within a system. When this method is used instead of a clear system description, or is levied arbitrarily across all components, system costs can escalate dramatically.

Sometimes a Component is Just a Component

In many applications a systems approach can be the key to saving time and costs when selecting thermal components. But frequently, system needs are very simple, so lengthy investments in detailed descriptions and analysis are not necessary. If the task is simply to keep water from freezing in a tank, then only a few simple thermal calculations are needed to select an off-the-shelf component. In the process of selecting a heater for such an application, the questions of how the water temperature will be sensed and how the heater will be controlled will easily be addressed and answered. Risk is low whether a very formal system development process is followed or not. The challenge of the system designer is not to convince everyone that all problems are systems problems. Rather, it is simply to ensure that the solution selected produces the emergent properties that satisfy the user need.

Or is it?

One final cautionary note is in order. Often, a perceived need is stated as a component need, but in actuality, cannot be satisfied from a component approach. Just as many good dishes are associated with one particular spice, relying on cayenne pepper alone will not result in a great bowl of gumbo.

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