Effective Innovation: using the Theory of Inventive Problem Solving to develop improved wet-wall gas quenches

Charles W. Lipp
Principle Consultant
Lake Innovation, LLC
Lake Jackson, TX 77566 USA

Abstract

Rapid quench cooling of gas streams with sprays is critical to a number of applications including flue gas conditioning, incineration, acid gas processing, and pyrolysis gas processing. The art and science of such designs is scattered throughout the academic and patent literature. State of the art computational models and robust spray measurements enable optimization of the performance of a specific quench design. Selecting the most appropriate design is an engineering problem routinely solved by the experienced designer; however, due to design trade-offs, the shortcomings are often incompletely resolved.

Using systematic innovation tools, such as Theory of Inventive Problem Solving (TIPS), can transform the design process by reducing complexity to the lowest level while achieving robust results. This method, known by the Russian acronym TRIZ, enables rapid development and exploration of innovative design space. The application of several key concepts and methods, including ideality, function analysis, substance field analysis, and innovation algorithm, are illustrated by a wet-wall industrial scale spray quench design. Two of the tools are emphasized and the results compared with existing patents. Describing the fundamental issues with a function diagram showing useful and harmful actions incorporates the most complete knowledge of the situation. A substance-field diagram showing the interaction of substances and fields (energy) narrows the innovative focus to the design conflict zone. With the abstract description of the problem refined, a systematic search for innovative solutions is used. These descriptions retain the essence of the problem without jumping to solutions. An algorithmic approach to inventive design is at least an order of magnitude more effective than the ubiquitous brainstorming. TIPS methodology is a practical means of understanding complex innovative problems and focusing the inventive efforts on the root problem.

Introduction

Wet wall Spray quenches are used in a wide variety of industrial applications including areas with high particulate loads. Numerous and diverse spray quench designs are used in the manufacture of cement, acid gas processing, pyrolysis gas processing, and hazardous waste incineration. Applications of the Theory of Inventive Problem Solving (TIPS), also known as by the Russian Acronym TRIZ, can improve the quality of designs. TIPS was introduced to the spray community at ILASS by Lipp, Kling and Christenson[1]. The TRIZ methodology provides a collection of tools to systematically analyze the design problem and identify families of solutions. Systematic approaches have been shown to generate a larger number of higher quality solutions than brainstorming. A team brainstorming session can yields 300 to 600 ideas with only 5% actionable potential solutions. This paper shows the use of the TRIZ tools coupled with axiomatic design methods to characterize the nature of the design conflicts and design space.

Background

Analysis and evaluation of spray quenches is based on Lagrangian calculations of trajectory, heat transfer, and evaporation, Lefebvre [2]. These models describe the physics of the system [3] based on gas heat and mass transfer limitations. Current CFD models such as Fluent 6.3[4] have capabilities to rapidly model all of these aspects of a spray quench. Conjugate heat and mass transfer are included in the models by others Elperin [5]. Many of the modeling challenges center on the range of scales from the droplet diameter to the hardware size that can span six orders of magnitude. Analysis of droplet trajectory depends on accurate inputs of the drop size distribution and velocity. The models required a sub-model of the drop drag coefficient to predict the drop trajectory. This is necessary to calculate the overall heat transfer coefficient for each drop along its path. Sprays from single fluid and two fluid atomizing nozzles are used for quenching. Pagcatipunan and Schick [6] described a methodology for evaluating design configurations. In many applications, these complex design cases are readily solvable with current tools. The challenge is to determine the “best” or “most ideal” quench design for a specific system.

The TRIZ methodology was developed in the former Soviet Union by Genrikh S. Altshuller [7] who recognized similar concepts being applied in patents in different technology areas. TIPS [7, 8, 9] uses a full description of several key concepts and methods including ideality, function analysis, substance field analysis, and innovation algorithm. This paper illustrates the application of TIPS by analyzing the fundamental issues of a spray quenching problem to develop innovate and improved designs. Application of TIPS enables a comprehensive analysis of the design issues and considerations. Often, the inventive process is a team effort. Problem solvers with experience, successes and failures, are advantaged by their experience but unconsciously limited to the familiar space of successfully-solved problems. To avoid being mentally trapped in the familiar ruts, by egos, and vocal team members, the use of TIPS abstracts the problem into function space, and then applies known solutions and decision matrices to narrow the area of search.

Analysis

This paper builds on the previous work [1] to explore a subset of spray quenches. Systems with high particulate load use a wet-wall design with recirculated quench liquid. Figure 1 shows a wet-wall design used in an incinerator system. Wet-wall designs intentionally have a portion of the spray contact the wall. The resulting water film on the wall removes particulate matter from the wall. The example system’s design parameters, specifications, and design degrees of freedom, are provided in Table 1.

Ideal quench design: Altshuller observed that systems tend to move in a direction where the useful actions are maximized and harmful actions are minimized or more preferably eliminated. The concept of ideality is the ratio of useful function to harmful actions, which include cost. The following were identified as ideal characteristics of a quench system. These characteristics are not achievable but do provide insight to the trade-offs that are make as designers.

- Zero pressure drop on the gas flow
- Zero pressure drop of the quench liquid
- Zero drop evaporation time
- Zero spray nozzles.

The last item seems counterintuitive because the implied the use of spray nozzles to achieve the primary useful result. For example, the weir quench [10] has no spray nozzles where the gas flow breaks-up the quench liquid. To some this exercise seems superficial but it is useful to allow a team to collect and unify the understanding of most commercially significant design problems.

A functional based description of the problem is a necessary step to abstract the key useful and harmful actions in the system. A function diagram of wet-wall spray quench visualizes the system objects, tools and the interactions, Figure 2. Rapidly cooling hot gas is the primary useful function of the spray quench. There are several engineering parameters needed to describe the rate of gas cooling; however, a functional description does not have engineering parameters. The rounded rectangles represent objects and lines represent actions in this diagram. Active verbs are preferred in describing the actions. Examples of functions from Figure 2 are, the spray nozzle disperses fluid and the spray nozzle disperses the quench liquid. Tools are categorized as a main tool or auxiliary tools according to their function and importance.

Harmful actions in functional diagram notations are shown in grey; light grey identify actions that are harmful and useful actions. The harmful actions, highlighted in the function diagram, Figure 2, show several issues. Drops striking the wall due to the drop trajectory and the influence of the hot gas on drop trajectory are two harmful actions. Additional harmful actions include the cooled gas mixing with the droplets, reducing or inhibiting the droplet evaporation; and incomplete mixing of the hot and locally cooled gas. An effective improved design must address all conflicts. Several adverse actions are shown by the medium grey arrows in include drops striking the walls and drops cooling only a portion of the gas. Some advantageous and adverse actions require several objects interacting to achieve the function. An example of a technical design contradiction is a small drop size is required to achieve the surface area and larger drop size is required to penetrate the flowing gas. Adverse actions indicated in the function diagram help design teams better understand the fundamental issues of the design and identify tradeoffs. A completed function map compactly provides a visual representation of the interaction of components without excessive attention to the engineering parameters of the design.

Part of our domain expertise as spray technology practitioners is in the design and selection of spray nozzles to achieve this essential function of creating a collection of drops that will evaporate to produce the desired cooling rate. The required science and methods of calculation of the heat transfer coefficient of individual droplets is well established. Sufficient drop surface area and evaporation are essential for all designs to achieve the main function(s). Often, the focus of designers is only on the required function enabled by the collection of drops. Obviously, a spray quench with inadequate drop properties will not achieve the primary useful function of rapidly quenching the gas. Standard engineering optimization tools are useful to optimize the cost, but these will not provide insight as to where to make changes to achieve breakthrough designs.

Table 1 summarizes the design specification and design degrees of freedom for this system. Axiomatic Design [11] approach provides valuable insights based on design axioms. In this case indicating an uncoupled system is possible given the excess number of design degrees of freedom over design specifications. Therefore, the system is underspecified having many solutions. Practical experience with this system confirms this conclusion. TIPS can be used to provide new solutions.

Results and Discussion

The functional diagram indicates two conflicts, uniform wetting of walls and uniform quenching of gas. These conflicts are shown in Figures 3 and 4 as substance field (SuField) diagrams, which abstract the function diagram to only the substances (S) and energy fields (F). Solutions, which segment these two conflicts, tend to be the most robust because there is little linkage between the systems, Geddes [12]. The solution to the first design conflict can be described in several ways, one is to assure a uniform wall coverage by the liquid film. In essence, the ideal is a uniform liquid flux. The inventive space to be explored is the additional of a new force to the system. Table 2 shows a list of commonly used “forces” or energy sources. The structure of the substance field diagrams determines the solution space using heuristics [3,5]. The second conflict is that the cooled gas inhibiting evaporation is due to the inadequate of mixing of the gas and drops. Industrial scale systems often involve ducts greater than 1 meter in diameter. In large ducts, spray penetration limits the quenching. A commonly used solution is to segment the liquid into smaller streams (requiring smaller nozzles) and distributing these nozzles over the cross-section [1]. The key difference between a dry wall quench (drop must completely evaporate to prevent any liquid from contacting the wall) and a wet wall quench is the severity of consequences of drops contacting the wall. Thus, the remaining conflict is that of drops uniformly mixing with the surrounding gas when the exit gas is approaching saturation. Table 3 describes the narrowed potential list of area to evaluate. Exploration of these zones depends on the specific project requirement and constraints to determine the most advantageous approach.

The last major TRIZ concept to be introduced is the evolutionary potential of an engineering system described by Mann [13]. Developments follow a typical S curve as described in Figure 5. Systems or products undergo many changes and transitions during their life cycle. Observations from diverse product life cycles have identified to 30 lines of evolution. Technology assessment wet-wall spray quench system using this approach resulted in the radar plot seen in Figure 6, which shows in yellow the current system, and in blue the evolution potential of the system. This not to say that all systems will develop to this state but there is a potential. This focuses the innovative questions and review of current practice to area with greater evolutionary potential. An example of one of the lines of innovation shown in Figure 6 is geometric evolution. The following four stages of geometric evolution are, point, 1 Dimensional, 2 Dimensional, and 3 Dimensional. Currently with nearly all quenches are designed as axis symmetric systems (2D) while, in reality, there is always some degree of 3D influence. Thus, there is innovative potential by incorporating the 3D character in the design.

Practical experience in applying these methods in teams with diverse skills provided a significant number of unique patentable solutions. By identifying specific areas of focus, the level of engagement of all individuals is very high. The strong ownership of the concepts by the team is critical to develop and implement solutions.

Conclusions:

The outcome of using TIPS methodologies in complex problem solving is a more complete and viable set of solutions. TIPS based tools are practical, productive, cost effective, and not just theory. The tools empower subject matter experts to develop inventive solutions rapidly and exhaustively. The function analysis, a most useful tool, enables the description of complex problems by visualizing interaction of design issues, resulting a deeper understanding of the core design questions. Applying design heuristics narrows the search space for solutions, enhancing the creative process of even the most creative person.

References

1. Lipp, Kling and Christenson, A fresh look at design of spray gas quench systems using the Theory of Inventive Problem Solving (TIPS) ILASS 2008 Orlando May 22, 2008
2. Lefebvre, A.H., Atomization and Sprays, Hemisphere Publishing Corporation, 1989, pp. 228-260
3. Sjenitzer, F., The evaporation of a liquid spray injected into a stream of gas, Chemical Engineering Science, 17, 309-322, 1962
4. Ansys.com(Fluent)
5. Elperin, T., Fominykh, A., Conjugate mass transfer during gas absorption by a filling liquid drop with internal circulation, Atmospheric Environment, 39 (2005) 4575-4582
6. Pagcatipunan, C., Schick, R., Maximize the Performance of Spray Nozzle Systems, Chemical Engineering Progress, December 2005
7. G. Altshuller, H. Altov, Lev Shulyak, And Suddenly the Inventor Appeared: TRIZ, the Theory of Inventive Problem Solving, Technical Innovation Center, Inc.; 2nd edition (May 1996)
8. Rantanen, K., Domb, E., Simplified TRIZ, CRC Press, 2002
9. Fey, V., Rivin, E., Innovation on Demand, Cambridge University Press, 2005
10. Galloway, et al, Quench Apparatus and method for the reformation of organic material, U.S. patent 6,613,127, 2003
11. Suh, N.P., Axiomatic Design Advances and Applications, Oxford University Press, 2001
12. Geddes, R.L., Rapid cooling for high temperature gas streams, US patent 3593968, 1971
13. Mann, D., Hands on Systematic Innovation, IFR Press 2007

Table 1. Wet-wall spray quench design overview

Design Specifications	Design degrees of freedom
Exit percent saturation	Water flow
Quench Duty	Pressure drop liquid
Percent excess water	Number of nozzles
Uniformity of exit gas temperature	Arrangement of nozzles
Quench Time	Design of nozzles
Design gas flowrate	Vessel volume
…	Gas velocity
	…
	…

Table 2. Listing of fields used in TRIZ based on Fey and Rivin

Category	Examples
Thermal	Infrared radiation, Convection, Temperature gradient
Chemical	Chemical potential, Surface energy
Mechanical	Frictional, Centrifugal force, Vibration, Pressure gradient, Gravitational, Acoustic, Fluid dynamic,
Electrical	Monopole, Dipole, Line charge, Line dipole, Traveling,..
Magnetic	Permanent, Magnetic dipole, Electromagnetic, ..

Table 3. Summary of ARIZ solution area for gas quenching

ARIZ Standard Solution number (9)	Description of standard solution	Applicability/comments
1.1.6	Action that is difficult to control within the constraints of the problem – use most intense action and excess removed	Yes—quench systems often use great excess of liquid to assure complete action
1.1.7	Add another substance connected to the first substance	Yes, potential
1.1.8	Field should have maximum or minimum intensity	Yes, potential
1.2.4	Add another field to system- if existing substances and fields must be maintained	Yes, electric field
1.2.5	If involving magnetic fields – use ferromagnetic	NA
1.1.1	Enhance the effectiveness and controllability of a system with an incomplete SuField by introducing missing (or new elements)	Potential- very broad question
2.3.1	The effectiveness can be enhanced by tuning or detuning of the frequency of a field action of the object or the tool	Yes, highly turbulent systems have broad spectrum of frequencies
2.3.2	The effectiveness can be enhanced by tuning or detuning of the frequency of a field action of the object or the tool	Yes, potential
2.3.3	When two actions are incompatible -- one action is performed during pauses on the other action	NA

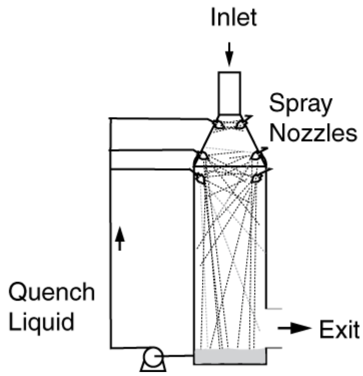

Figure 1. Schematic diagram of wet-wall spray quench

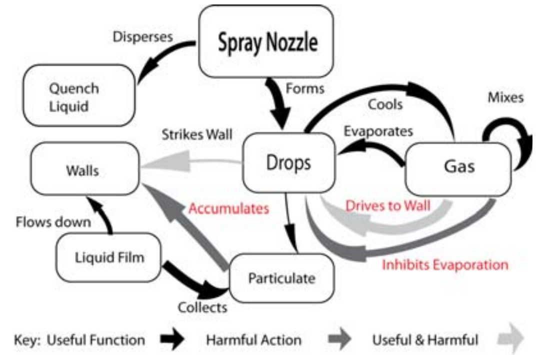

Figure 2. Function diagram of wet wall quench

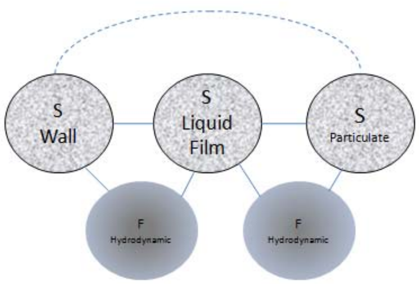

Figure 3. Substance-Field diagram wall-particle conflict

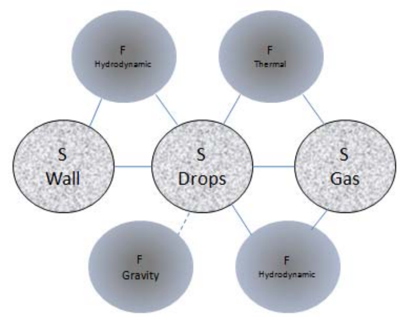

Figure 4. Substance-Field diagram gas cooling conflict

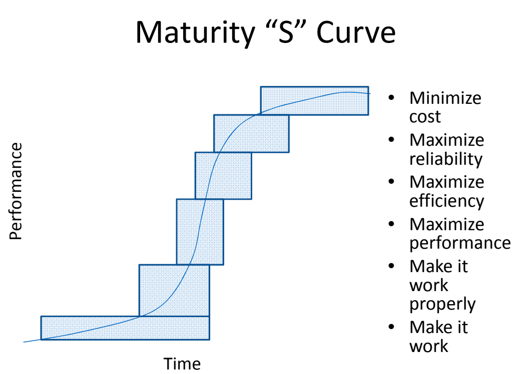

Figure 5. "S" curve technology evolution

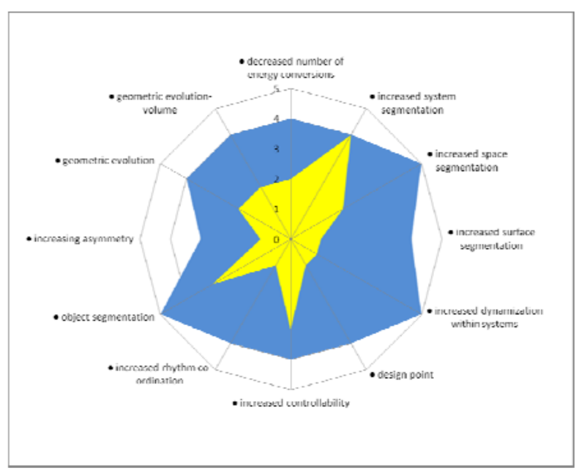

Figure 6. Evolutionary potential Diagram