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A novel *Friday 13th* risk assessment of fuel-to-steam efficiency of a coal-fired boiler

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HIGHLIGHTS

- Stochastic effects revealed as cause of failure of efficiency in coal-fired-boiler.
- Process is continuous mix of successful and unsuccessful operations.
- Can be used to assess vulnerability to failure and improve costs and reliability.
- Immediate interest to manufacturers and operators of boiler equipment.

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ABSTRACT

A novel *Friday 13th* (*Fr 13*) risk assessment is used for the first time to investigate the fuel-to-steam efficiency of a coal-fired-boiler (CFB). The aim was to quantitatively determine the risk to reduced CFB efficiency in the face of naturally occurring random (stochastic) changes in key parameters. Data from a new commercial plant in East Java, Indonesia are used. The approach was to define an underlying unit-operations model based on the indirect heat-loss method, together with an efficiency risk factor (p). Process behaviour is simulated using a refined Monte Carlo (Latin Hypercube) sampling of 20 key input parameters that include coal feed and quality. The CFB is expected to operate at an efficiency of η=82.82%. Below 77.82% the process is characterized as 'fail' due to the greater coal needed to produce steam quantity and quality, and the potential for damage to the boiler. Results reveal an underlying risk of 73 failures in CFB efficiency per 10,000 operations. This equates on average to three failures each year over a prolonged period. This new information cannot be obtained from alternative hazard and risk approaches. A number of changes to the CFB to cut efficiency failures are illustrated using *Fr 13* methodology. It is shown to be a practical design tool for improving process reliability and costs. A major benefit is that it can be used in design synthesis and analysis. Findings will be of benefit to operators and manufacturers of boiler equipment.

1. Introduction

Unexpected (surprise) process failures are sometimes attributed to human error, or, 'leaky' plant fittings; this is especially true of circumstances where investigators are not able to identify a clear cause in otherwise well-operated and well-maintained plant (Cerf and Davey, 2001; Davey, 2011). Indeed, high impact-low probability failures are now a major practical and theoretical concern for governments and companies of almost every size (Anon, 2012).

Davey and co-workers have demonstrated that these failures can be caused by a combination of within system, random (stochastic) changes in key parameters. Their hypothesis is that these changes can sometimes accumulate unexpectedly in one direction to leverage significant change in product or process (Davey et al., 2013). They suggested that this underlying risk of vulnerability to surprise failure due to naturally occurring random changes in key process parameters be titled *Friday 13th syndrome* (Davey and Cerf, 2003), or more generally, *Fr 13* risk, to indicate the unexpected and surprise nature of the event (Davey et al., 2013).

Importantly, *Fr 13* differs significantly from alternative hazard and risk methods because this random parameter is explicit in it. Alternative risk methods include *Microbiological risk assessment* (CAC, 1998), Hazard Analysis Critical Control Point (HACCP), *HAZ*ard and *OP*erability (HAZOP) and *Reliability Engineering* (O'Connor et al., 2002). Drawbacks with these (discussed elsewhere e.g. Davey, 2010, 2011; Davey et al., 2013) include that they are often semi-quantitative, but also that they do not address random effects because this critical parameter in these is omitted,

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or strictly, 'hidden'. Significantly therefore, these methods cannot be used to understand or reduce random effects, with either more study or measurement (Anderson and Hattis, 1999; Vose, 2008). This is true also of the recent assessment of Riverol and Pilipovik (2014) who addressed process 'failure frequency' with a case study on milk pasteurization. Importantly, this was not predicated on widely used unit-operations principles in chemicals processing (*see* for example Foust et al., 1980; Schwartzberg and Rao, 1990; Ozilgen, 1998; Wankat, 2007) and therefore a limitation is that it might not be generalizable; it has much in common with *Reliability Engineering*.

In contrast, a benefit with *Fr 13* assessments is that both the facts about the process and the effects of random changes in parameters are separated (Hoffman and Hammonds, 1994; Ria and Krewski, 1998; Davey et al., 2013). This is more mathematically correct and is highly advantageous because it permits the effect of each to be studied.

The principle of a *Fr 13* assessment is that it is predicated on the underlying unit-operation, together with a practical definition of process failure and a refined Monte Carlo (r-MC) sampling (Davey, 2011). The refinement used is Latin Hypercube sampling (Vose, 2008). Significantly, published findings from *Fr 13* assessments have generally underscored that alternative risk methods can actually downplay risk when a process is considered over a long period of operations.

Published studies include demonstration of a sudden process change from sterile milk to non-sterile product (Davey and Cerf, 2003; Cerf and Davey, 2001); from stable to unstable operation with fermenter 'washout' (Patil et al., 2005; Patil, 2006); from clean to unclean (Clean-In-Place) processing (Davey et al., 2013, 2015; Chandrakash, 2012); from potable to non-potable water (Abdul-Halim and Davey, 2015; Davey et al., 2012; Davey and Abdul Halim, in press); and more generally, from safe to unsafe (Davey, 2011; Davey et al., 2012; Nolan and Barton, 1987).

Crucially, these studies underscore that *Fr 13* does not need to imply actual breakage of plant or its shutdown; it can also be an unexpected failure to meet vital product reliability and safety criteria. Overall the general and quantitative picture from this emerging research method is that apparently well-operated and well-maintained continuous operations are in fact an instantaneous mix of success and failure.

1.1. This study

Here a *Fr 13* assessment of the fuel-to-steam efficiency of a continuous coal fired boiler (CFB) is presented for the first time. The aim is to gain insight and new knowledge about the effects of naturally occurring random changes in CFB process parameters that could give rise to unexpected loss (failure) of fuel-to-steam efficiency, and; to investigate practical interventions that could be demonstrated to reduce this vulnerability to loss. Data from a commercial CFB in East Java, Indonesia are used (E. Simbolon, pers. comm.). The justification for this research is that it will aid greater understanding of factors that contribute to efficiency in CFB and increase confidence in operation of plant. Because CFB is a major global unit-operation for steam and power generation it is expected findings will have a wide application. The nature of the research is model development and simulation.

CFB efficiency is that portion of the input energy from the fuel that is utilized as steam. It is commonly termed 'fuel-to-steam efficiency'. Low efficiency in CFB operation requires higher fuel consumption to produce a particular steam quantity and quality, higher operational and maintenance costs, and; is a cause of potential damage (rupture) of boiler tubes because of undetected scale build-up and overheating. As a result, the CFB must be shut down, inspected and potentially repaired.

A unit-operations CFB model is first developed and solved using a traditional single value assessment (SVA). This is then contrasted with results from the new *Fr 13* simulation using r-MC sampling together with a newly defined efficiency risk factor (p). The established simulations are used as a quantitative tool with realistic large-scale data to evaluate practical re-design and targeted physical changes for maintaining efficiency. The work will be of interest to operators and manufacturers of boiler equipment.

2. Materials and methods

A new (2-year post-commissioning) commercial CFB in East Java, Indonesia, was selected for investigation because critical process information was available. This CFB consists of two boilers in parallel operation with steam production of 150 t h^{-1} each. Indonesian sub-bituminous coal is used to produce high pressure steam of 96 bar at a temperature of 540 °C for steam power generation.

A simplified process flow diagram showing the unit-operation is presented as Fig. 1. The coal is delivered by ship and unloaded and stored in closed storage from where it is fed to the boiler using a belt-conveyor. It is crushed and pulverized. The pulverized coal is collected in silos. The silos are equipped with rotary valves and speed controllers to measure and control the coal fed to the boiler.

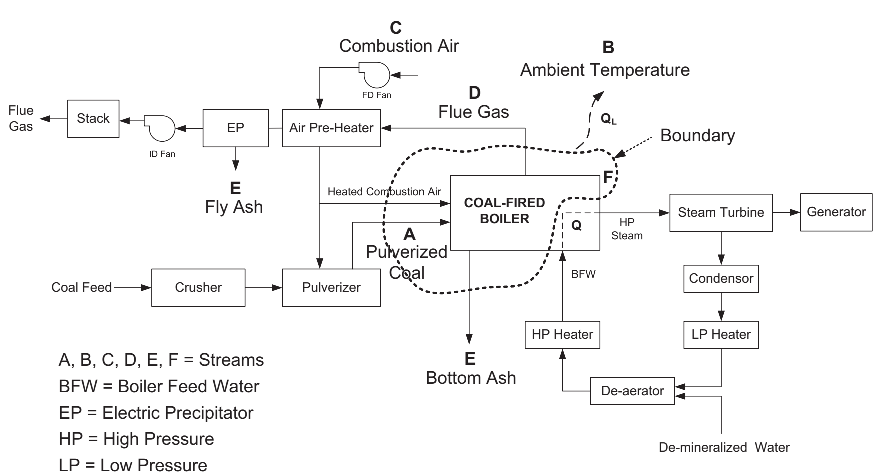

Fig. 1. Process flow diagram of a CFB unit-operation, East Java, Indonesia.