Applied Thermal Engineering 76 (2015) 292–300

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

An automated procedure for the optimal positioning of guide plates in a flow manifold using Box complex method

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HIGHLIGHTS

- Tackles practical fluid flow problem of flow distribution.
- Formulation as an optimization problem.
- Coupling of CFD and optimization for automated procedure.
- Demonstration of robustness of approach.

ARTICLE INFO

Article history:
Received 10 May 2014
Accepted 8 November 2014
Available online 18 November 2014

Keywords:
Fluid flow
Heat recovery systems
Manifolds
Guide plates
Optimization
Computational fluid dynamics

ABSTRACT

Flow splits and manifolds are encountered in many industrial processes such as heat recovery systems to feed reactant streams and take out product streams. Depending on the application, the flow distribution among the several outlets may be equal or unequal. In this paper we describe a computational method for achieving desired flow distribution in a flow manifold using optimally positioned guide plates. For multiple outlet streams, determining the orientation of the guide plates is a non-trivial problem. The positioning of one guide plate will have an effect on the flow rate through the other outlets. This effect cannot be estimated from simple models but can be calculated using computational fluid dynamics (CFD) simulation of the corresponding flow problem. However, a conventional CFD simulation cannot predict the optimal location of the guide plates. In view of this, we pose the flow distribution problem as a constrained optimization problem and use a well-established algorithm coupled to a computational fluid dynamics (CFD)-based flow solver to develop an automated procedure for the optimal positioning of the guide plates. The robustness of the procedure is illustrated for both equal and unequal flow distributions in a one-inlet, four-outlet manifold with guide plates of fixed and variable lengths.

1. Introduction

Many engineering equipment such as process heat exchangers ([1]), cooling modules for electronic equipment ([2]), fuel cells ([3,4]), nuclear reactors ([5]), catalytic converters ([6]), paper machine headboxes ([7]) etc., need division of a single fluid stream into several branching streams. Uniform or desired flow distribution among several possible flow paths is essential to run processes under optimal conditions. A case in point is the flue gas system of a coal-fired thermal power plant. Here, the flue gas from the economizer will have to be split into two unequal streams, one going to a primary air heater and the other going to a secondary air heater. The exit gases from these heat recovery systems are recombined and are split again into four equal streams to be fed to a bank of four electrostatic precipitators (ESP) for particulate removal. Often, redundancy is built into the system for reliability by having two sets of primary and secondary air heaters and eight particulate removal systems. While under design conditions, all the systems would be operating; under maintenance or breakdown conditions, the flow will have to be diverted to the actual units which are operational. While the off-design condition is met through valves and guide vanes, optimal flow distribution in the manifolds is achieved by header design and strategically placed guide plates to maintain uniform flue gas flow rate to each stream of ESP.

An example of unequal flow distribution from a manifold arises in supersonic-combustion ramjet combustors (scramjet) which are considered as one of the promising propulsion systems for

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http://dx.doi.org/10.1016/j.applthermaleng.2014.11.015
1359-4311/

hypersonic transport. In these combustors, it is necessary that the fuel–air mixture remains supersonic throughout. Heat addition by combustion to a supersonic flow decreases the Mach number and if the heat released by the combustion exceeds a certain critical value, the Mach number in the engine falls to unity and the flow becomes thermally choked [8]. This choked flow may in turn cause a shock train to form at the engine inlet. This phenomenon, known as unstart, creates a large amount of drag and radically reduces the performance of the engine at high flight Mach numbers [9]. This problem is usually avoided through distributed heat release using axially staged injection depending upon the combustor geometry and flow conditions. To achieve this, it is essential to have different amounts of fuel to pass through different outlets. Usually, this is achieved by using a flow control valve installed in each of the outlets which introduces a significant undesirable pressure loss.

A number of analytical approaches have been reported in the recent literature on the header design and flow distribution in branching channels which take account of pressure losses due to wall friction and bends and pressure gains (or losses) due to expansion and contraction through one-dimensional continuous or discrete mathematical models of mass and momentum balance equations for uniform or non-uniform header cross-sections ([10–18]). Nowadays, computational fluid dynamics (CFD) techniques are being used increasingly for three-dimensional analysis of flow manifolds. Several geometrical strategies for attainment of uniform mass flow through all the exit ports of a distribution manifold have been proposed including tapering/enlargement of the header cross-sectional area, variation of the cross-sectional areas of the exit channels, provision of baffle tubes, fins, protrusions, deflector plates and cavities ([19,20,1, 21–25,5]). The case of unequal flow rates appears not to have been dealt with explicitly in the literature.

There is increasing tendency to use optimization techniques for the design of equipment to achieve improved performance or reduced costs under specified constraints. For example, the shape of the headbox was optimized by Park et al. [7] using CFD and genetic algorithm wherein the shape of the headbox was represented by a Bezier curve. In a similar vein, CFD based optimization studies were performed using the downhill simplex method [26], artificial neural networks [27] and genetic algorithms [28] for reducing the pressure drop in cyclone separators. Optimization algorithms ([29,30]) are usually classified into traditional algorithms such as gradient-based methods and non-traditional optimization algorithms such as genetic algorithms, simulated annealing etc. Although gradient-based optimization algorithms are more efficient, many real-world optimization problems use computationally expensive simulation packages to evaluate the objective function, thereby making it difficult to evaluate the derivative information. Evolutionary algorithms such as genetic algorithms need a fairly large population of possible solution to start the optimization process [29]. They are also known to scale poorly with increasing number of parameters to be determined. Another approach is to use meta models, constructed from prior CFD simulations using such methods as response surface methods, in the optimization step in place of CFD computations ([26,31]). While this reduces the computational effort during optimization, the solution depends on the accuracy of the meta-model. In a multi-parameter problem, the computational effort required to generate an accurate meta-model itself may become very expensive. For example, the number of CFD simulations required for a meta-model for four parameters, each requiring only three levels (e.g., low, medium and high values of each parameter), will be 3^4 or 81 in a full factorial method. This number increases rapidly if either the number of levels (for increased accuracy) or the number of parameters increases. For example, for four levels, the number of solutions would be 4^4 or 256 and for a three-level, eight-parameter problem, the number would be as high as 3^8 or 6561. Also, the meta-model needs to be updated using the results from the CFD simulation to improve its accuracy and actual numerical simulations also required to be carried out [32]. Simplex methods, such as that of Box's complex method [33], which is applicable for constrained optimization problems, appear to be more effective in certain cases. A comparison between the genetic algorithm and Box's complex method [33] for a three-parameter problem involving determination of the optimum thickness of the composite plates [34] showed that Box's complex method required one-fourth of the numbers of calculations required by the genetic algorithm. In addition, it is relatively easy to implement and is well-suited for non-linear problems having inequality constraints.

Against this background, the objective of the present work is to explore the possibility of applying the Box complex method to the flow distribution problem in a manifold, specifically to the problem of positioning guide plates optimally in a manifold/header to achieve a desired flow distribution. To this end, the problem is posed as a constrained optimization problem with an objective function of minimizing the deviation of the flow rate from the desired flow rate in each leg. The decision variables in the optimization problem are the orientation of guide plates. The optimal solution, in the form of optimal orientation of the guide plates in each flow path, is to be obtained through the Box complex method. It is shown that such an

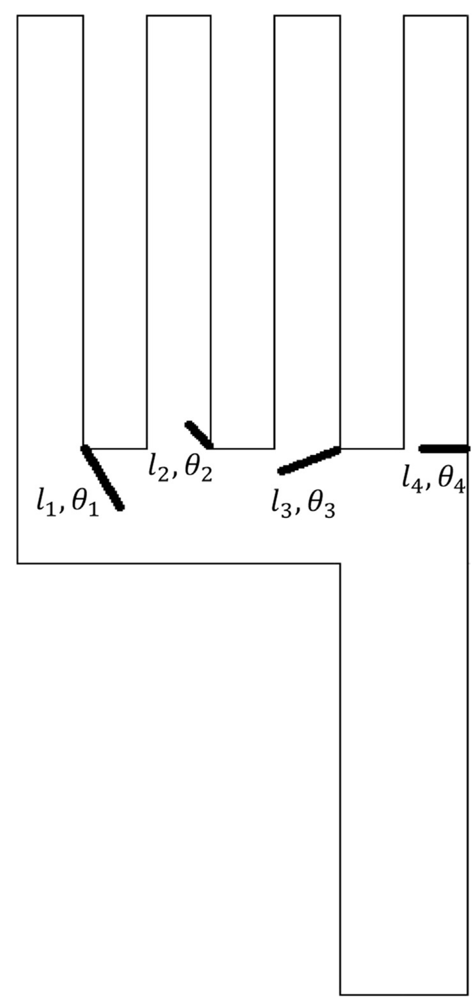

Fig. 1. Schematic of flow distribution manifold with arbitrarily oriented guide vanes.