NATIONAL TECHNICAL UNIVERSITY OF ATHENS
School of Mechanical Engineering
Fluids Section
Laboratory of Thermal Turbomachines

PhD Thesis

DESIGNING THERMO-FLUID SYSTEMS USING GRADIENT-BASED OPTIMIZATION METHODS AND EVOLUTIONARY ALGORITHMS

Evgenia A. Kontoleontos

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Supervisor: **Kyriakos C. Giannakoglou,** Professor NTUA

Abstract

This PhD thesis focuses on the development of optimization methods for the design of thermo-fluid systems based on criteria related to fluid mechanics and/or heat transfer. This thesis is concerned with the continuous adjoint method, as the basic component of gradient-based optimization methods and evolutionary algorithms, which are stochastic population-based search methods. The hybridization of gradient-based and stochastic methods is also presented. Regarding the adjoint methods, in addition to shape optimization, a new topology optimization method for CFD applications with or without heat transfer is presented. Thus far, the optimization methods developed in the context of previous PhD theses in PCOpt/LTT was used along with objective functions related to the aerodynamic performance of the systems, without laying emphasis on heat transfer effects. In this PhD thesis, objective functions in which heat transfer plays an important role are used. Therefore, the application domain, apart from turbomachinery applications, extends to the design of heat transfer systems, such as geothermal power plants, ground source heat pump systems and the design of some key components of them, such as heat exchangers.

The developed adjoint methods are based on the continuous adjoint formulation proposed in a previous PhD thesis (A. Zymaris, NTUA), where, for the first time in the literature, the continuous adjoint to the turbulence model equation(s) was presented so as to compute exact sensitivity derivatives in case of turbulent flows. The present thesis extends this method to incompressible flows with heat transfer, by focusing on the accuracy of the computed sensitivity derivatives. For this purpose, the formulation of the continuous adjoint equations for incompressible flows with the addition of the energy equation is presented. Regarding the formulation of the adjoint problem, the resulting adjoint momentum and turbulence model equation (here, the Spalart-Allmaras one) are coupled to the energy equation, even though the primal ones are decoupled to the energy one. The first point of novelty of this thesis is the continuous adjoint method for incompressible flows with heat transfer, which is presented for the first time. The method is applied mainly to ducts and heat exchangers. The objective functions take into account viscous losses and exchanged heat.

In the present PhD thesis, emphasis is laid to the reduction of the computational cost of the

optimization procedure. In standard gradient-based optimization methods, within each cycle, the flow and the adjoint equations are solved in a segregated manner, followed by the shape update using the gradient of the objective function. Over and above, this thesis presents the one-shot optimization technique, applied to the aforementioned problems. The one-shot technique is based on the simultaneous solution of the flow, adjoint and shape correction equations and reduces the overall computational cost. In order to further reduce the turnaround time of the optimization, the one-shot algorithm was ported on NVIDIA Graphics Processing Units (GPUs), by using the PCOpt/LTT's experience in programming on GPUs. The gain from the use of the one-shot is superimposed to the gain in efficiency due to the use of GPUs.

Apart from shape optimization, the present thesis is extended to topology optimization problems in fluid mechanics and heat transfer. In fluid mechanics, topology optimization is used for designing flow passages, connecting predefined inlets and outlets, with optimal performance based on selected criteria. A variable porosity field, to be determined during the optimization, is the means to define the optimal topology. The computation of a real-valued porosity field must be performed over an extended domain. Based on local porosity values, parts of the domain can be solidified and the remaining areas define the optimal flow passage. In topology optimization, the porosity values at each node of the computational grid stands for the design variables. Since the number of design variables is equal to the number of nodes, which depending to the problem might be very high, the adjoint method is the, by far, most appropriate optimization technique. In the present thesis, a topology optimization algorithm for incompressible, laminar and turbulent flow problems including heat transfer, was developed. The formulation of the primal and adjoint equations for laminar and turbulent flows with heat transfer, by introducing new porosity dependent terms, is presented for the first time in the literature. In turbulent flows, the formulation is developed for low-Reynolds number turbulence model. The topology optimization algorithm is used for the design of ducts/manifolds for minimum total pressure losses and/or maximum temperature rise between the outlet from and the inlet to the domain. In the topology optimization of manifolds with more than one outlets, constraints similar to those used in industrial applications are imposed. Among them, constraints on the desirable volume flow rate per outlet section and/or on the mean temperature of the outgoing flow, are worked out.

Regarding the stochastic optimization methods, aiming at the solution of computationally demanding optimization problems, the present PhD thesis is concerned with the combined use of an Asynchronous Evolutionary Algorithm (AEA), which was initially presented in a previous PhD thesis (V. Asouti, NTUA) together with a gradient-based method. With the proposed hybridization, the developed adjoint methods and software are being used as local search tools. The AEA is a non-generation-based algorithm, which, as such, maximizes the exploitation of the available computational resources. The hybridization of the AEA with a local search method gave rise to a new asynchronous metamodel-assisted memetic algorithm (AMAMA), which performs better than AEA. When this new algorithm is used to solve multi-objective optimization problems, all individuals that enter the current front of non-dominated individuals are automatically selected to undergo local search. The local search method includes the computation of the objective function gradient with respect to the design variables, the refinement of the individual using steepest-descent and the re-evaluation of the refined individual, which may displace or not the current individual.

In multi-objective optimization problems, in order to further reduce the CPU cost, a new scheme for the computation of the sensitivity derivatives in the memetic algorithm, according to which the adjoint equations are solved only once, instead of as many times as the objectives, is proposed. This scheme is based on the synthesis of the objectives into a scalar function multiplied by appropriate coefficients. The latter is another novelty of this PhD thesis. The proposed algorithm is used to optimize heat exchangers and turbomachinery cascades. It is concluded that the implementation of local search which transformed the AEA to an asynchronous memetic algorithm further reduces the computational cost of the optimization.

The AEA was also used for the optimization of heat transfer systems, such as geothermal power plants and ground source heat pump systems. Regarding the geothermal power plants, the design and the development of an Organic Rankine Cycle (ORC) prototype, using low temperature geothermal resources, was the main goal of the European project LOW-BIN (Efficient Low Temperature Geothermal Binary Power, FP6). CRES (Centre for Renewable Energy Sources and Saving, Greece) was the coordinator of this project and the contribution of PCOpt/LTT, as reflected in this thesis, was to provide expertise on optimization methods for the design of an efficient, low-cost ORC. The exploitation of low temperature geothermal fields ($65^oC<T<90^oC$) requires the development and optimization of organic Rankine cycle technologies. During the ORC optimization, the research focused on the identification of the optimal organic fluid and the optimal heat exchanger types. Regarding the organic fluids, the purpose was to choose among R-134a, R-410A, R-407C and R-600a. On the other hand, flat plate and shell-and-tube heat exchangers were compared. The project resulted in the manufacturing and installation of an ORC prototype for low temperature geothermal resources. This produces 200kWe using the geothermal field at Simbach in Germany. The second application in the field of geothermal energy is concerned with the design of ground source heat pump systems (GSHPs) using the AEA. In the European project GROUND-MED (Advanced Ground Source Heat Pump Systems for Heating and Cooling in Mediterranean, FP7), coordinated by CRES, PCOpt/LTT through this thesis, contributed to the desing of optimal GSHPs with maximum efficiency and miminum heat exchangers' surface.