Introduction

The research described in this thesis deals with a practical industrial problem: to understand the physical phenomena occurring in a turbine stage with upstream flow injection from the outer casing and to provide guidelines for minimizing energy loss associated with the injection. To the present date very few reports have been published in the literature with respect to this topic. Some authors have explored the usage of flow injection or suction to minimize the secondary losses but these studies, mostly experimental, were conducted for very particular cases, such as linear cascade models and simple uniform flow injection configurations, which are quite different from the real situation found in the industry. This study was conducted by using state-of-the-art computational codes capable of modeling problems as close as possible to the actual situation. The results obtained by the numerical simulations were complemented with experimental data obtained through measurements in a turbine stage rig available at the university. Taking advantage of the robustness, accuracy and speed of the numerical flow solvers at hand an optimization tool based on the latest technology in *genetic algorithms* was developed. Finally, the information from the numerical data and the optimization tool were used for designing a swirler to control the injection flow angle.

The paragraphs that follow provide a short summary of previous work related to the current research and also a background for the chapters of the thesis. The discussion was divided into three topics: flow injection, blade lean and genetic algorithms. Blade lean is a design technique that can be used for reducing secondary losses near the end walls by simply rotating the blade pivoted on its root. In this work blade lean is also explored as a means of minimizing the energy loss associated with injection.

Flow Injection

Flow injection and suction are techniques that have been applied to the improvement of the efficiency of modern gas turbines. For instance, Nie et al. [1] proposed the usage of steady micro air injection from the casing (0.045% to 0.056% of the compressor main flow) to improve the stability of a three-stage low-speed axial compression system. The authors explored various injection configurations and found out that the performance of the compressor could be improved by reducing the axial gap between injection and blade leading edge, reducing the radial penetration of injector, increasing the amount of injected air and directing the injection jet towards the pressure side of the blade. Girgis et al. [2] investigated the effect of secondary air injection as means of improving the performance of a transonic turbine stage. Experiments and numerical calculations conducted by the authors revealed an improvement in efficiency of approximately 0.45% for every percent of flow with 20^0 tangential injection of upstream disk purge flow. Radially injected flows did not produce the same improvement. Biesinger and Gregory-Smith [3] conducted five-hole probe measurements in order to investigate reduction in secondary flows and losses in a turbine cascade with upstream tangential boundary layer blowing. According to their experiments, the effect of increasing blowing is first to thicken the inlet boundary layer, giving greater secondary flow and more loss, and then as re-energisation of the inlet boundary layer takes place together with increasing counter streamwise vorticity, the passage vortex is progressively weakened, with a corresponding reduction in loss. The injection angle was also analyzed by the authors, the low angle being more effective than the high angle, keeping the blowing jet closer to the end wall at inlet to the cascade. The authors, however, did not find any net gain with flow injection. Improvements in the jet injection geometry as well as combining injection with other features such as film cooling or disk root leakage air are among the suggestions given for achieving gain in terms of overall performance. Funazaki et al. [4] proposed a study to investigate the reduction of secondary flow effects in a linear cascade by use of air suction from the end wall. The authors concluded that end wall suction successfully controlled the passage vortex, resulting in significant reduction of the cascade loss.

In some kinds of steam turbines for combined cycle or geothermal power plants, the primary objective of flow injection is to improve the efficiency of the thermodynamic cycle. The injection flows (from 5 to 15% of main mass flow rate) from steam generators are introduced between turbine stages. As a counterpart of the gain due to the injection of steam, the loss associated with the mixing of the secondary and the main streams may incur in additional pressure loss. The upstream steam injected from the outer casing is usually at a different temperature and velocity than the main flow. Since the injected steam and the main flow are not completely mixed in the vicinity of the stator leading edge, pitchwise and spanwise variations of the mass flow and the unsteadiness of the inlet flow angle occur (Fig.1). Such variation would change the turbine stage operating conditions, affecting the blading flow pattern and efficiency. Therefore it is necessary to investigate such disturbances upstream of the nozzle vanes, which in the present study are denominated “inlet distortion”. Hirai et al. [5] conducted numerical simulations for investigating the effect of circumferential positions of inlet hot streaks to a single stage turbine. The pressure loss due to unsteady flow for a transonic rotor with inlet total pressure distortion was also analyzed. Moser [6] investigated distorted flow conditions caused by asymmetric exhaust and by ribs in the radial and circumferential direction by using pneumatic probes. Zeschky and Gallus [7] determined the effects of the outlet distortion provided from the stator exit on the turbine rotor by using three-dimensional hot-wire and pneumatic probes. The formation of the passage vortices in the rotor were found to be strongly influenced by the non-uniform stator outlet flow which caused the accumulation of low-energy fluid in the rotor wake close to mid-span.

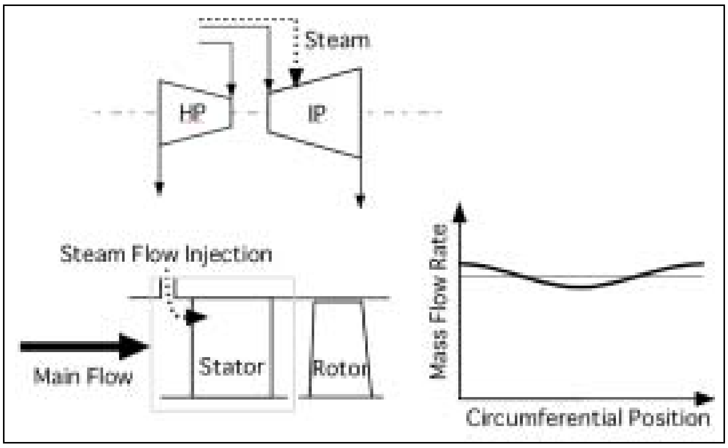


Figure 1 - Flow injection schematic diagram.

In some turbine stage configurations the flow is tangentially injected upstream of the stator. In such case, the injection flow may be directed to the suction side of the stator at some circumferential positions and to the pressure side of the blade for other locations. This circumferential variation of the injection angle may cause a significant impact on the flow field, i.e., the variation in the outlet flow angle and increase in loss. In order to quantify these effects experimental studies have been conducted in a single stage turbine test rig, shown in Fig.2. The secondary flow is injected into two pipes (*inlet 1* and *inlet 2*), driven into a scroll and exits through the injection slot. Main flow is sucked from upstream providing the rotation for the rotor. Detailed information on the test facility as well as experimental results can be found in the report of Kamata et al. [8].

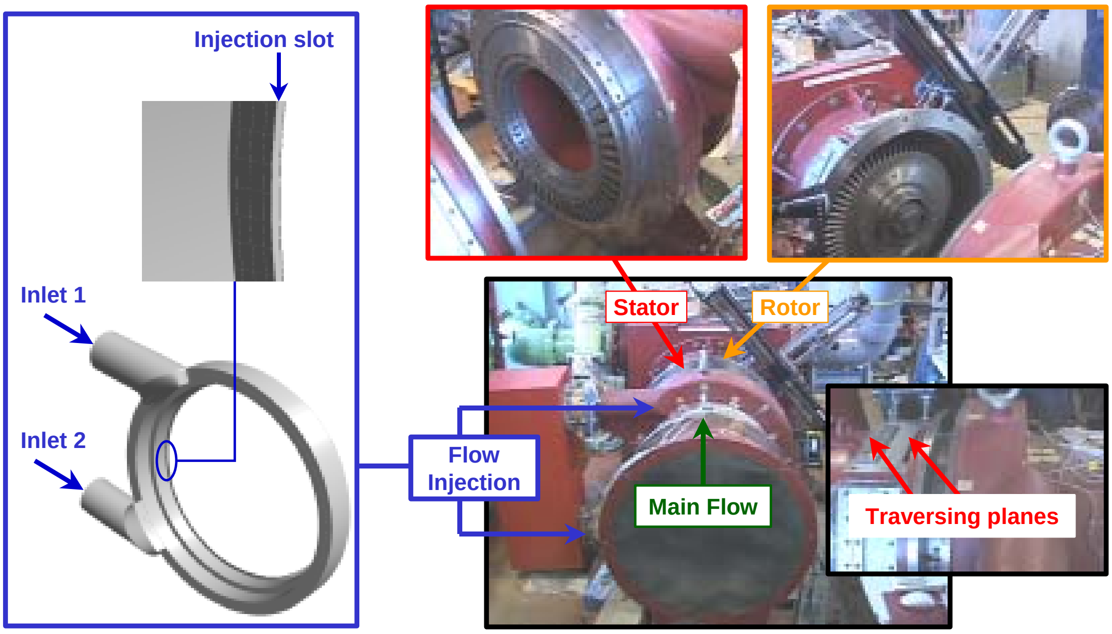


Figure 2 - Experimental Facility at Iwate University.

Figure 3 shows results obtained by tuft visualization as well as numerical simulation. The stator and rotor blades were removed and air was blown into *inlet 1* and *inlet 2*. The tufts indicate symmetric injection flow angle distribution from the top and bottom half sections. The circumferential variation of the injection flow angle (*β*) seen in the figure is expected to cause the machine to operate at different loss levels, showing better performance at some circumferential locations than others. Therefore it seems desirable to investigate the effect of *β* on the flow pattern and possibly develop a control device to maintain the optimum injection flow constant along the circumferential direction.

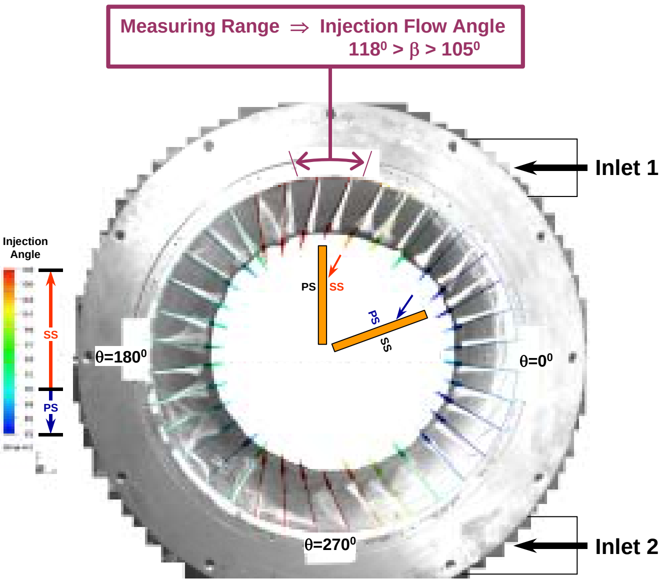


Figure 3 - Injection flow angle distribution (tuft visualization and numerical calculation results).

Blade Lean

Blade lean, or non-radial blade stacking, can be beneficial for the improvement of turbine blade design. For low hub/tip radius machines, blade lean can be useful for increasing stage reaction. This axisymmetric effect is explained in terms of the streamline curvatures (Δr) induced by lean by Denton and Xu [9] and is illustrated in Fig.4. The authors proposed a simple model for showing qualitatively the effects of the added radial blade force (*Fr*) due to lean in sharing between a change in radial pressure gradient and a change in streamline curvature acceleration.

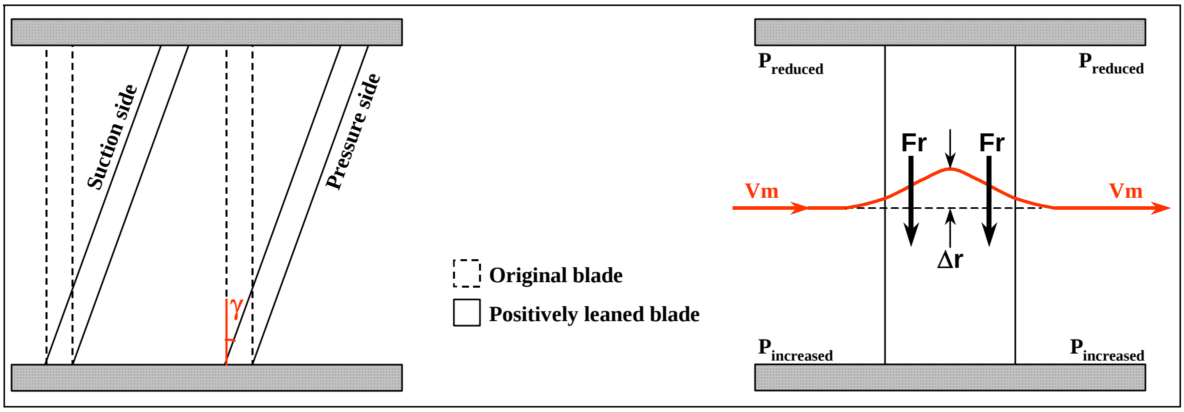


Figure 4 - The effect of blade lean on streamline curvature [9].

Blade lean may also be used to control end wall losses. Static pressure contours at an axial cutting plane in the blade passage reveals that, at low aspect ratios, different blade stackings may be considered as moving the blade within an almost frozen pressure field [9]. Figure 5 shows that for the unleaned blade the root section has been moved into a region of high velocity and hence its loading is reduced while the tip section has been moved into a region of high velocity and its loading increased. In other words, positive blade lean may contribute for reducing secondary losses near the root with a counter effect near tip. In order to eliminate the undesirable effects near the tip section, a bowed blade type or compound lean is often adopted in the design of gas turbine blades. It consists of positively leaning the blade near root and negatively leaning the blade near tip with a spanwise curvature to smoothen the transition from one lean direction to the other. Figure 5c shows that compound lean can be more effective than simple positively lean in terms of end wall secondary loss reduction. There is a counter effect, however, when compound leaned blades are used. The numerical results obtained by Wang et al. [10] show that bowing the blade does reduce the loss near the end walls but also increases it near mid-span. A number of different explanations related to such trend have been reported in the literature [11-13] but common agreement is yet to be reached, as mentioned by Denton and Xu [8].

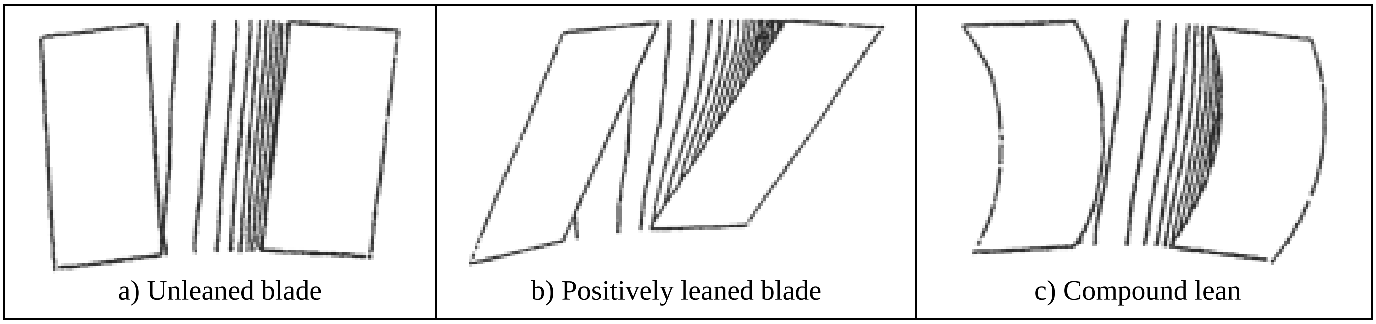

a) Unleaned blade
b) Positively leaned blade
c) Compound lean

Figure 5 - Static pressure contours through a turbine stator with different stackings (1/4 axial chord). Suction surface to right of passage (Denton and Xu [9]).

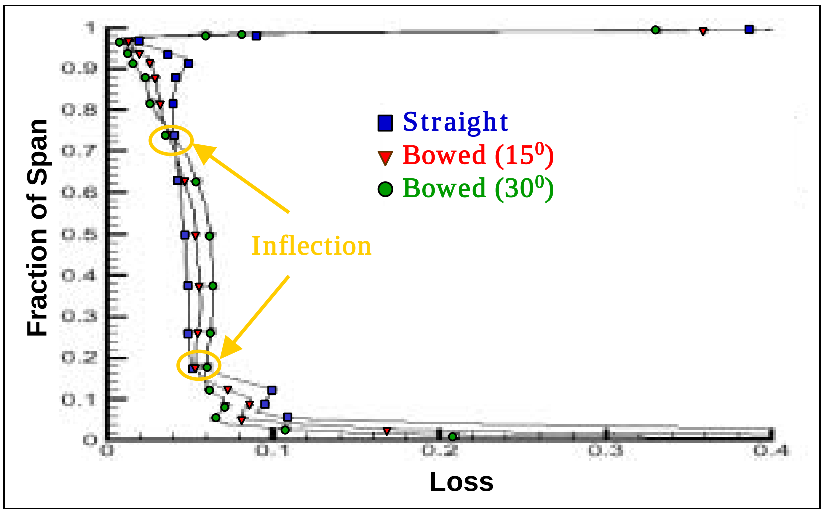
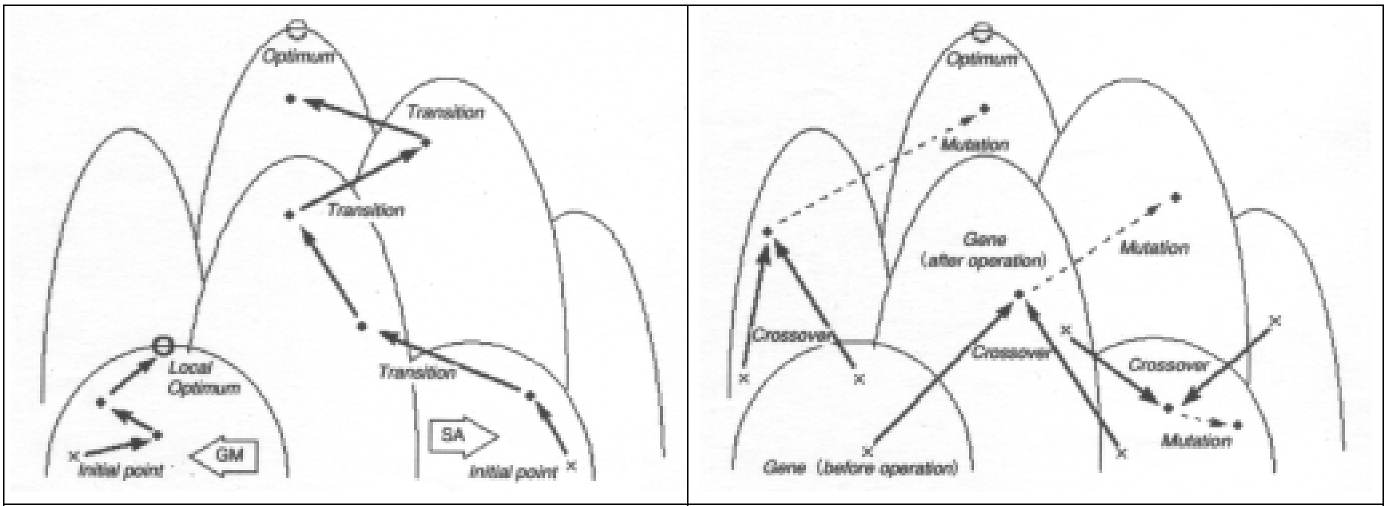


Figure 6 - Distribution of pitchwisely averaged loss coefficient along span at outlet (Wang et al. [10]).

Genetic Algorithms

The studies above described show that controlling the injection flow angle and the blade lean angle can be effective in reducing the loss. However, none of the cited reports offered an analysis of both situations at once, i.e., the combined effects of injection flow angle and blade lean angle for the same case. The assessment of the optimum values for β and γ requires the development of a search tool. If only the flow field around the stator is to be considered, the objectives of the optimization can be though as minimizing the energy loss and minimizing the difference between the exit flow angle for the datum (no lean and no injection case) and each case.

There are a great number of optimization techniques for single objective functions available in the literature. The most common class of methods are the gradient-based or *hill climbing* algorithms. These algorithms are fast and can be quite efficient when well-behaved target functions are considered. However, when more complex functions having multiple modes are to be optimized the usage of such conventional methods is not recommended. Instead, stochastic methods such as Genetic Algorithms (*GA*) are preferable. These methods search for the optimum point in many directions, avoiding premature convergence at local peaks or plateau regions, which may not represent the global maximum of the search domain. If multi-objective optimization problems are to be solved, conventional methods have an even greater disadvantage in comparison with *GA*. Most of these methods cannot handle the true multi-objective case since they were developed for searching only one objective. The problem is usually converted and solved as a single objective optimization task, which may substantially compromise the solution. Apart from the fundamental advantages of using *GA* for multi-objective problems, the method is also attractive in the computational point of view. A *GA* code consists of basic mathematical operations that can be parallelized in a very straightforward and efficient manner.



a) Schematic optimization process for the gradient-based method (*GM*) and simulated annealing (*SA*).

b) Schematic optimization process for evolutionary algorithms.

Figure 7 - Schematic optimization process for gradient-based methods, simulated annealing and genetic algorithms (Obayashi [17]).

A comparison between *GA* and other optimization methods for aerodynamic shape design was performed by Obayashi et al. [14]. The other methods were a gradient-based method (*GM*) [15] and simulated annealing (*SA*) [16], in which the design is updated if a randomly disturbed one is better. Figure 7 [17] shows the schematic optimization process for each one of the methods and Fig.8 [14] presents the convergence history obtained for all methods. The authors found that the results obtained by *GA* (2.480) outperformed the *GM* (1.716) and *SA* (1.728) methods by a large difference. Although both *SA* and *GA* are stochastic methods and are therefore capable of getting out of local extrema, *GA* presented the best results. The reason, according to the authors, is because *GA* searches an optimum in parallel from a population, whereas *SA* allows only a single perturbation at each time step. Thus, the results of *GA* depend on the initial guess less than that of *SA*.

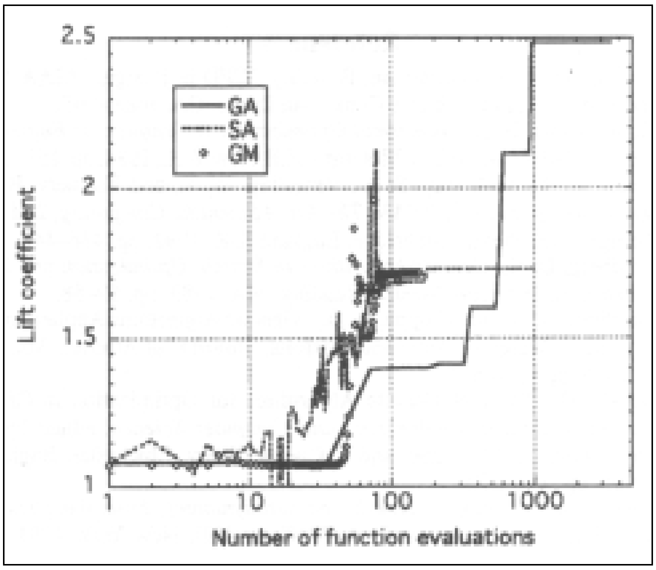


Figure 8 - Computation of optimization histories among GM, SA and GA (Obayashi et al. [14]).

The substantial increase in computational costs for obtaining a better solution by use of *GA* has motivated many researchers to develop acceleration techniques for alleviating such disadvantage. One approach proposed by Giannakoglou and Giotis [18] is to use artificial neural networks. Sefrioui and Periaux [19] propose a hierarchical genetic algorithm. The authors suggest the usage of a multi-layer model in which a great number of coarse numerical calculations are performed for exploration and then some are selected and upgraded to an intermediate model. The flow field is solved for these selected cases using a finer model. From these solutions fewer are selected and upgraded to the top level where precise numerical simulations are performed. The authors show that the calculation time was reduced by a factor of 3 when using their alternative approach for shape optimization of a converging-diverging nozzle for transonic flows. Wang et al. [20] applied the methodology of Sefrioui and Periaux [19] for parallel processing of *GA* using an 8-CPU PC-cluster, obtaining a speed-up ratio of 4. Quagliarella and Vicini [21] developed a hybrid genetic algorithm code. Their approach uses a hill-climbing algorithm combined with a *GA* code. The local gradient search not only provides a refinement of the solution obtained by the optimizer but also reduced the CPU time substantially.

Chapter Structure

Chapters 1 and 2 of this study provide an attempt to explain the physical effects happening when secondary flow is injected upstream of the nozzle vanes through numerical simulations. Chapter 1 concentrates on the flow field around the stator only, providing a parametric study for identifying potential flow injection design variables to be optimized. These include the injection flow rate, the injection slot width, the distance between the injection slot and the leading edge of the stator and blade lean. Chapter 2 is devoted to the description of the numerical simulation of the flow field in the turbine stage. In Chapter 3, a study of the flow field inside the scroll is presented. The injection flow angle variation is quantified and a swirler for controlling β is developed by use of multi-objective *GA*. Chapter 4 introduces the development of a *GA* based single objective genetic algorithm code and its application to a gas turbine related problem. In Chapter 5 the development of a multi-objective genetic algorithm (*MOGA*) code is presented. The code was applied to the optimization of the injection flow angle and blade positive lean angle as well as the two-dimensional design of the blades for the swirler.

Originality of the Present Work

The present research is believed to be one of the first attempts to thoroughly investigate the physical effects of upstream flow injection from the outer casing in a turbine stage. The parametric study for the flow injection variables can be useful for steam turbine designers since almost no information of such kind is available in the literature. Without any prior knowledge the choice of the values for each of the flow injection parameters can only be done by trial and error tests, which may incur high operational costs. This work attempts to clarify the physical phenomena associated with these design variables and provide suggestions for minimizing the energy loss associated with flow injection.

The second part of the thesis deals with optimizations using genetic algorithms. The single and multi-objective genetic algorithm codes were based on the most recent methodologies available in the literature. Genetic algorithms were invented almost half a century ago and throughout the years many enhanced versions were proposed. However, only a few years ago this method has been used for solving complex three-dimensional flow optimization problems. The contribution of the present work for the *GA* community can be thought of the application of the technique to the selected optimization tasks. The implementation of the particular commercial software adopted in the present work to a multi-objective GA code for solving three-dimensional flow injection related problems is believed to be unique.

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