

# Fast Calculation of Real Fluid Properties with the New IAPWS Standard on the Spline-Based Table Look-Up Method (SBTL) and its Application in CFD

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**Long Abstract**

## Introduction

The simulation of non-stationary processes with CFD is acquiring growing importance for the development and optimization of turbomachinery. In these computationally intensive simulations, precise and extremely fast fluid property calculation algorithms are required. For this purpose, table look-up methods are frequently applied. Discrete values of the required properties are calculated from accurate equations of state and are stored in look-up tables. During the CFD simulation, properties are determined from these look-up tables with simple interpolation algorithms. With local algorithms, such as bi-linear or local bi-cubic interpolation, properties within a cell of the look-up table are calculated from adjacent values only, as opposed to global methods, where all tabulated values are used. Although local algorithms are easily implemented, they do have their deficiencies. Bi-linear interpolation requires comparatively large look-up tables to represent the fluid properties with acceptable accuracy and does not provide continuous first derivatives. Local bi-cubic interpolation overcomes these problems, but the calculation of the required inverse functions is computationally intensive as it requires the evaluation of transcendental functions. Moreover, to achieve the desired accuracy over the entire range of state, the look-up tables are frequently prepared with variable distances between the nodes. This requires extensive cell search algorithms during the property calculation and decreases the computing speed. In order to provide fast and accurate property calculation algorithms for CPU-intensive complex simulations, the Spline-Based Table Look-up Method (SBTL) was developed in this project. Through the use of this method, existing equations of state, such as the industrial formulation IAPWS-IF97 for water and steam, can be reproduced with high accuracy and minimal computing-time consumption.

## The IAPWS Standard on the Spline-Based Table Look-up Method (SBTL)

The SBTL method combines global bi-quadratic spline interpolation with specialized coordinate transformations and simplified search algorithms. In this way, existing fluid property formulations (equations of state) can be reproduced with high accuracy and high computing speed, whereas the size of the look-up tables is minimized.

In a project of the International Association for the Properties of Water and Steam (IAPWS) the SBTL method has been applied to the industrial formulation IAPWS-IF97 [1] and the scientific formulation IAPWS-95 [2]. SBTL property functions for water and steam have been generated [3] for the independent variables specific volume and internal energy ( $v, u$ ) for the entire range of validity, including the metastable states, of the respective formulation. With these functions thermodynamic and transport properties, thermodynamic derivatives, and backward functions are calculable in the single-phase, two-phase and

metastable regions. Backward functions of the variables pressure and specific volume ( $p, v$ ), and internal energy and entropy ( $u, s$ ) are calculated with complete numerical consistency to the spline functions of ( $v, u$ ). The properties calculated from the SBTL property functions are in agreement with those of the underlying IAPWS standard within a maximum relative deviation of 10 to 100 ppm depending on the property and the range of state. Consequently, the differences between the results of process simulations using the SBTL method and those obtained through the use of the corresponding IAPWS formulation are negligible. Computations from the ( $v, u$ ) spline functions are more than 200 times faster than calculations with IAPWS-IF97 and are more than 400 times faster than calculations with IAPWS-95.

The International Association for the Properties of Water and Steam (IAPWS) has issued the "Guideline on the Fast Calculation of Steam and Water Properties with the Spline-Based Table Look-Up Method (SBTL)" [4] as an international standard. In addition to the spline and inverse spline functions of ( $v, u$ ), ( $p, v$ ), and ( $u, s$ ), the IAPWS Guideline also contains SBTL property functions of pressure and enthalpy ( $p, h$ ) along with the corresponding inverse functions of pressure and temperature ( $p, T$ ), pressure and entropy ( $p, s$ ), as well as enthalpy and entropy ( $h, s$ ).

### **Application of the SBTL Method in CFD**

In order to demonstrate the applicability of the SBTL method, the developed algorithms have been implemented into the CFD software TRACE of the German Aerospace Center (DLR). As a result, the computing times for flow simulations of steam turbine stages considering real fluid behavior are reduced by a factor of 6 to 10 in comparison to the calculations based on IAPWS-IF97. In comparison to CFD-calculations where steam is considered to be an ideal gas, the computing times are increased by a factor of 1.4 only through the use of the SBTL method. Consequently, the newly developed SBTL method enables the accurate consideration of real fluid behavior in complex CFD simulations.

For generating SBTL property functions, the software FluidSplines has been developed. This software enables the application of the SBTL method to any property function and fluids other than water and steam. Projects are being planned to apply the SBTL method to carbon dioxide, dry air, humid air and combustion gas mixtures. The resulting property functions can be used in advanced CFD simulations for compressors and gas turbines.

The SBTL method, its application in CFD, and software for generating SBTL functions are presented.

### **References**

- [1] IAPWS, Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam (2007), available at <http://www.iapws.org>.
- [2] IAPWS, Revised Release on the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use (2009), available at <http://www.iapws.org>.
- [3] Kunick, M., Kretzschmar, H.-J., Property libraries with the Spline-Based Table Look-Up Method (SBTL) applied to IAPWS-IF97 and IAPWS-95 for CFD and other computationally intensive process simulations, available at <http://www.thermodynamics-zittau.de>.
- [4] IAPWS, Guideline on the Fast Calculation of Steam and Water Properties with the Spline-Based Table Look-Up Method (SBTL), available at <http://www.iapws.org>.